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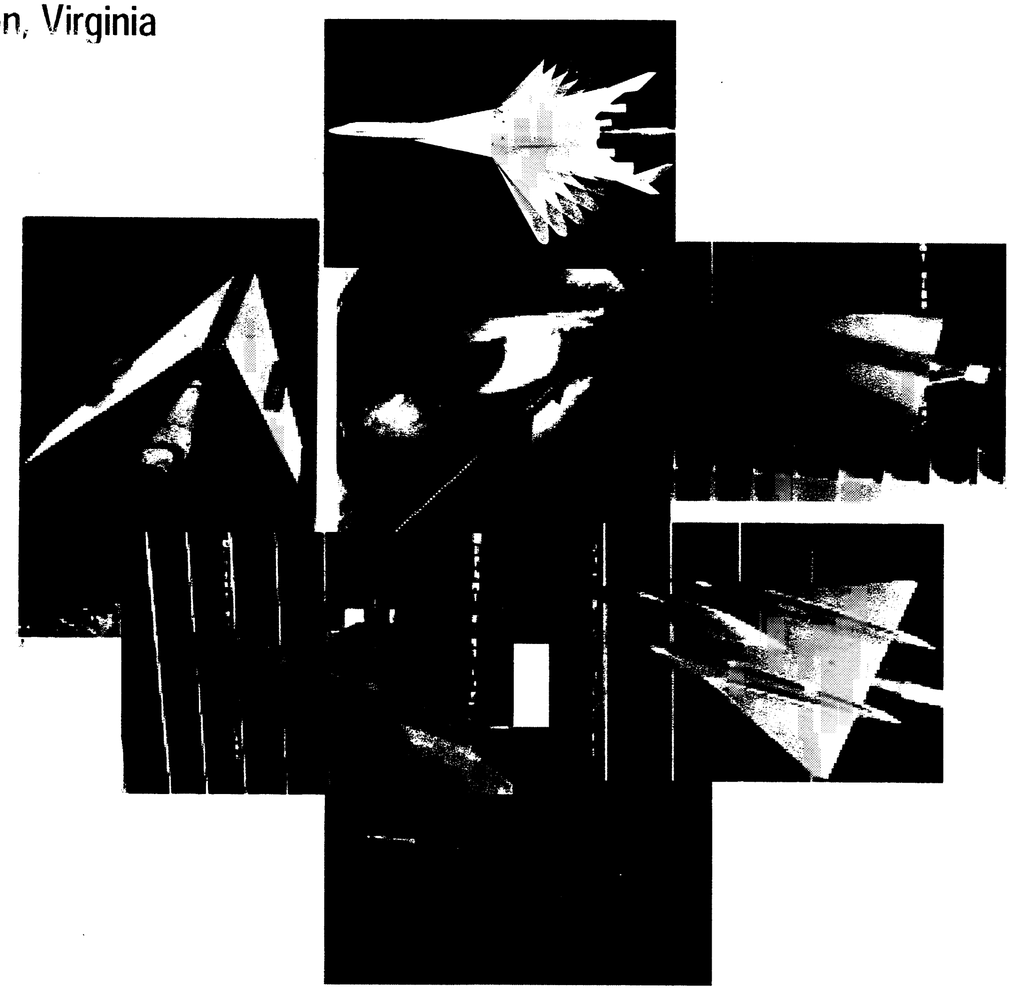

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# AERODYNAMIC DESIGN OPPORTUNITIES FOR FUTURE SUPERSONIC AIRCRAFT (I. L.)

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## Abstract

*A discussion of a diverse set of aerodynamic opportunities to improve the aerodynamic performance of future supersonic aircraft has been presented and discussed. These ideas are offered to the community in a hope that future supersonic vehicle development activities will not be hindered by past efforts.*

*A number of nonlinear flow based drag reduction technologies are presented and discussed. The subject technologies are related to the areas of interference flows, vehicle concepts, vortex flows, wing design, advanced control effectors, and planform design. The authors also discussed the importance of improving the aerodynamic design environment to allow creativity and knowledge greater influence.*

*A review of all of the data presented show that pressure drag reductions on the order of 50 to 60 counts are achievable, compared to a conventional supersonic cruise vehicle, with the application of several of the discussed technologies. These drag reductions would correlate to a 30 to 40% increase in cruise L/D for a commercial supersonic transport.*

## 1.0 Introduction

In contrast to subsonic and transonic aerodynamics, supersonic aerodynamics remains an immature discipline due in large part to the erratic starts and stops by the aeronautic community since the 1940s [1]. A graphical representation of the history of supersonic research is presented in figure 1. Significant levels of supersonic aerodynamic research began in the 1940s and during both the 1940s and 1950s the research emphasis was on basic shapes and concepts focusing on the development of an understanding of this new flight regime. However, with the introduction of linear theory in the 1950s and computers in the 1960s there was a marked decline in the basic research and an increase in the application of linear theory to the design of supersonic aircraft. This change in emphasis was undoubtedly influenced by the challenge of the new frontier – efficient supersonic flight.

The design efforts within the United States of the 1960s were directed towards the B-70 Bomber Program and the Supersonic Transport (SST) Program and did achieve notable success in increasing the supersonic cruise Lift-to-Drag ratio. Following the

termination of these programs the supersonic research declined significantly but was reborn in the mid 1970s as the NASA Supersonic Cruise Research (SCR) Program. The SCR Program achieved some success but was terminated in the mid 1980s and once again the supersonic research efforts declined significantly. In the early 1990s the NASA High Speed Research (HSR) Program was started. The HSR Program lasted approximately five years and was terminated in 2000 without a sufficient advancement in aerodynamic technology to achieve economic viability of the vehicle.

Another aspect of the SST, SCR, and HSR programs was their focus on both laminar flow [2] and sonic boom [3, 4] technologies and the respective design capability. These programs identified both of these technical areas as critical to the success of future supersonic cruise vehicles. However, as with the aerodynamic performance efforts of these programs, neither the laminar flow nor the sonic boom capabilities have reached a significant level of maturity. As a result, the ability to design a vehicle to achieve an acceptable level of sonic boom or significant levels of laminar flow does not currently exist.

A closer examination of the major supersonic research programs within the United States since 1960 shows that for the most part they had similar challenges and goals, and as expected they have produced similar results. However, there were a few technical innovations and technical diversions to the predictable path of the major programs. A graphic comparing several of these items is shown in figure 2 [1]. The most notable innovation was the work of R. T. Jones on the oblique wing concept in the 1970s [5]. Jones is also noted for his work with multiple fuselages in the 1970s. An interesting technical diversion is represented by Phenninger's work from 1988 [6], which has been routinely referenced in discussions of advanced supersonic cruise vehicles. The subject concept combines multiple fuselages, arrow wing, strut bracing, and laminar flow in a simplistic manner using a superposition framework. Unlike the work of Jones, Phenninger's concept is notional and has not been subjected to critical analysis or testing.

A review of the information presented in figure 2 show that both the oblique wing concept of Jones and the concept of Phenninger claim significant improvements, which are due primarily to assumed high levels of laminar flow. The same is true for the conventional delta wing concept presented by Harris in reference [1]. As mentioned previously there has been little advancement in the ability to achieve and maintain supersonic laminar flow in an operational environment. Therefore, it is doubtful if any of the projections presented in figure 2 will be realized for the subject concepts.

Despite the efforts of many engineers and scientists there has been minimal progress in improving the supersonic aerodynamic performance of a commercial supersonic transport vehicle from that achieved by the end of the SST Program in 1970. The inability to improve on the 1960 and 1970 performance level is not surprising when it is noted that despite the more than 30 years of research the preferred design of 2000 closely resembles the preferred design of 1970, see figure 3. A further review of the history of these programs indicates that one reason for the similarity in design has been the continued reliance upon 1960-1970 era linear theory based understanding and design philosophy as represented in figure 4 [7] and the assumption that laminar flow will be achievable.

The following sections of the paper will focus on aerodynamic opportunities for aircraft designed for efficient supersonic flight. These opportunities are centered around technologies and design concepts focusing on the reduction of pressure drag. These concepts include but are not limited to nonlinear based surface shaping, nonlinear-based redistribution of volume (i.e., nonlinear area rule), nonlinear-based redistribution of lift (i.e., advanced planforms), advanced flow/aerodynamic control technologies, and interfering flow fields (eg., nacelle-wing and body-wing interference).

## 2.0 Nomenclature

| | |
|---|---|
| AR | aspect ratio, $b^2/S$ |
| b | wing span, ft. |
| c | airfoil chord length, ft. |
| $C_D$ | drag coefficient, Drag Force/qS |
| $C_{D,o}$ | zero lift drag coefficient, Zero Lift Drag Force/qS |
| $\Delta C_D$ | change in drag coefficient from zero lift drag, $C_D - C_{D,o}$ |
| $\Delta C_l$ | change in rolling moment coefficient from baseline wing |
| $C_L$ | lift coefficient, Lift Force/qS |
| $C_{L\alpha}$ | lift curve slope, evaluated at zero lift, per deg. |
| $C_M$ | pitching moment coefficient, Pitching Moment/$qSc_{ref}$ |
| $C_N$ | normal force coefficient, Normal Force/qS |
| $C_p$ | surface pressure coefficient, $(p-p_o)/q$ |
| $C_Y$ | yawing moment coefficient, Yawing Moment/qSb |
| $c_{ref}$ | reference chord length, ft. |
| HSR | High Speed Research |
| K | zero lift pressure drag correlation parameter, $C_{Do}/\tau^2 AR$ |
| l | configuration length, ft. |
| L/D | lift to drag ratio |
| LE | leading edge |
| LT | linear theory |
| m | position of airfoil maximum thickness , expressed as fraction of local chord, r/c |
| M | Mach number |
| $M_N$ | component of mach number normal to the wing leading edge, $M\cos\Lambda(1+\sin^2\alpha \tan^2\Lambda)^{.5}$ |
| NL | non linear |
| p | static pressure, psf |
| $p_o$ | freestream static pressure, psf |
| q | dynamic pressure, psf |
| QSP | Quiet Supersonic Platform |
| r | airfoil maximum thickness position, ft. |
| Re | Reynolds number |
| S | wing reference area, $ft^2$ |
| SCR | Supersonic Cruise Research |
| SST | Supersonic Transport |
| t | wing airfoil thickness, ft. |
| $\alpha$ | angle of attack, deg. |
| $\alpha_{fus}$ | angle of attack of the fuselage, deg., |
| $\alpha_N$ | angle of attack normal to the wing leading edge, $\tan^{-1}(\tan\alpha/\cos\Lambda)$ |
| $\beta$ | Mach number parameter, $(M^2-1)^{.5}$ |
| $\beta\cot\Lambda$ | wing leading edge sweep parameter, |
| $\delta$ | fuselage rotation angle, deg. |
| $\delta_F$ | flap deflection angle, positive leading edge down, deg. |
| $\Lambda$ | wing leading edge sweep angle, deg. |
| $\tau$ | airfoil thickness parameter, expressed as fraction of local chord, t/c |

Superscripts

| | |
|---|---|
| l | lower surface |
| u | upper surface |

## 3.0 Fundamental Aerodynamics

Prior to a discussion of the opportunities and technologies that will improve the supersonic aerodynamic performance of cruise vehicles it important to develop an understanding of the fundamental supersonic aerodynamics characteristics. At supersonic speeds, the dominant aerodynamic challenge is reducing drag and not creating lift. Recognizing this fact allows the designer to concentrate on aerodynamic drag in the design process.

A further review of the aerodynamic characteristics of supersonic flight shows that for a majority of flight conditions more than half of the lift is produced by compression pressures acting on the lower surface and that there is an equivalent amount of pressure drag and friction drag acting on the vehicle. These characteristics are unique to supersonic flight and are not present for flight at subsonic and transonic speeds. Another observation of supersonic flight is that all forces acting on the vehicle vary linearly with angle-of-attack, for low lift conditions, consistent with supersonic cruise. The only exceptions to this rule are for a high aspect ratio arrow wing (i.e. high trailing edge sweep angle). An arrow wing will typically have nonlinear lift and pitching moment effects due to spanwise flow at the trailing edge of the wing. Despite the existence of linear forces and moments at supersonic speeds the flow and local loading on a supersonic flight vehicle is highly nonlinear. These nonlinear effects provide the designer with the opportunity to create additional nonlinear loading effects that can be used to reduce the drag of this class of vehicles. To better understand these effects a discussion of supersonic drag and arrow wing aerodynamics are provided in the following two sections.

### 3.1 Aerodynamic Drag

Supersonic drag reduction research and aerodynamic design continues to be hindered by the characterization and terminology used by the community to discuss drag. A review of the information presented in figures 4 and 5 highlights these issues. Figure 4 represents the linear theory and slender body theory based descriptions and explanations of drag and vehicle design that were originally developed between the 1940s and the 1960s. These concepts continue to be used to the present day. The data of figure 4 indicate that drag is composed of a variety of terms such as friction drag, thickness wave drag, lift wave drag, and lift vortex drag and that each of these drag terms is a function of the vehicle slenderness ratio, b/2l, and Mach number, as represented by the Mach number parameter ($\beta$). The reliance by the community on this description of supersonic drag severely restricts the design space because the vehicle is driven to a low slenderness ratio (b/2l) or very high wing sweep in order to balance out the Mach number effect. In essence, the design guidelines are to minimize wave drag (lift and thickness) and induced drag (lift vortex) but restricts the designer to using a long and slender, highly swept vehicle. This design approach does not account for the use of interference fields, low leading edge wing sweep, high aspect ratio wings, and strong shocks to reduce drag.

An alternate approach to drag reduction makes use of interference fields, and at times will maximize these fields, to reduce drag. It is interesting to note that the differences in these two design philosophies have been discussed since the 1940s as can be seen in a comparison of the works of Busemann from 1935 [8] and Jones in 1947 [9]. Additional discussions of supersonic drag reduction concepts can be found in references [3-5, 7, 10].

A more realistic view of the drag at supersonic speeds indicates there are only two naturally occurring forces acting on a vehicle moving through a fluid. These are the force that acts tangent to the surface and the force that acts normal to the surface. In the context of aerodynamics these forces are induced by shear or friction forces and pressure forces which correlate to friction drag and pressure drag as noted in figure 5. The relative magnitude of these two terms will change with vehicle shape, angle-of-attack, Mach number, and Reynolds number. The friction drag term may be a result of a laminar boundary layer, a turbulent boundary layer, or a mixture of laminar and turbulent boundary layers. The pressure drag acting on the vehicle may be a result of attached flow, organized vortex flow, separated flow, or a combination of all three. The key to achieving drag reduction is not based on the type of flow on a vehicle, rather by a management of the forces induced by the flow. It is a mistake to arbitrarily choose a preferred flow type for design because this limits the resulting vehicle shape.

Despite the known limitations and inaccuracies of linear theory it continues to dominate design decisions. An example of these inaccuracies is documented in the work of Ulmann and Dunning from 1952 [11] in which they discuss the "unrealistic drag peaks at flow conditions where the free stream Mach line is coincident with the wing leading edge or coincident with the ridge line, is very inaccurate". Ulmann and Dunning also discuss the drag force as being composed of a friction term and a pressure term only. It is unfortunate that the more straight forward descriptions of drag were not adopted by the community. To expand on these points and to discuss the differences between linear-theory based design and the natural flow based design approach, a discussion of the aerodynamics of symmetric delta wings follows. The data to support the following discussion is presented in figures 6 and 7 and was taken from the work of Wood in 1988 [12].

Presented in figure 6 are plots of the zero lift pressure drag correlation parameter (K, $C_{Do}/\tau^2 AR$) against the wing leading edge sweep parameter ($\beta \cot \Lambda$) for symmetric delta wings with diamond airfoils and NACA 4-digit airfoils, top and bottom plots of the figure, respectively. The zero lift pressure drag, correlation parameter is a linear theory based parameter that accounts for the effect of both wing aspect ratio and wing airfoil thickness on zero lift pressure drag (i.e., wave drag). However, the direct relationship between zero lift pressure drag and either aspect ratio or the square of the wing airfoil thickness is not a constant as documented in reference [12]. It should be noted that additional nonlinear analysis presented in reference [12] show that the linear theory predicted relationship between zero lift pressure drag and either AR or $\tau^2$ varies in a nonlinear fashion that is a function of Mach number, wing planform, and airfoil shape.

Linear theory and nonlinear theory (full potential) predicted drag values for the diamond airfoils, top of figure 6, show markedly different trends with increasing $\beta\cot\Lambda$ and position of airfoil maximum thickness position (m). Results are presented for airfoils with maximum thickness position that varies from .2 chord to .5 chord. Note the peaks in the linear theory curves, as referenced by Ulmann and Dunning. The first peak occurs when the Mach line is coincident with the maximum thickness line and the second peak is when the Mach line is coincident with the wing leading edge. While it has been documented repeatedly for the past fifty years that the variation in linear theory predicted zero lift pressure drag with Mach number (for a given delta wing) is misleading, the design criteria for wings and airfoil selection has been driven by these linear theory trends. In contrast, both the nonlinear theory results presented in figure 6, and available data, shows a smooth and continuous variation in zero lift pressure drag with Mach number. The nonlinear analysis for both the diamond airfoils and NACA 4-digit series airfoils (bottom of figure 6) show similar results due to changes in airfoil maximum thickness position and Mach number and/or sweep. The nonlinear analysis show that airfoil selection is an important factor in zero lift drag for values of $\beta\cot\Lambda$ less than 0.50 and greater than 0.80. For values of $\beta\cot\Lambda$ between 0.50 and 0.80, which is typical for a supersonic cruise vehicle, airfoil profile has a minimal impact on zero lift drag. This observation allows the designer to rely upon other criteria and constraints for airfoil selection. Despite the large difference between the linear theory and nonlinear theory predictions it is interesting to note that both predictions show large variations, greater than 200%, in zero lift drag due to airfoil maximum thickness position. However, a review of the literature failed to uncover design activities that made use of alternate airfoils that had a maximum thickness less than 0.40 or greater than 0.50.

As mentioned previously, the pressure loading on a wing in supersonic flight may be dominated by lower surface compression loading. This observation is counter to linear theory that assumes that the total lift force on a wing at all conditions is evenly distributed between the upper and lower surfaces. The linear theory assumption provides highly optimistic and misleading drag reduction benefits due to wing camber and twist. The fact that the naturally occurring loading on a wing at supersonic speeds is biased by the lower surface loading severely restricts the ability to reduce pressure drag of a lifting surface through wing shaping. To document these characteristics in more detail, an overview of the lifting characteristics of delta wings at supersonic speeds is presented in figure 7 [12]. The data presented in the two plots of figure 7 were extracted from existing experimental data. The chart on the left presents the combinations of $M_N$ and $\alpha_N$ in which the loading on a delta wing will have an upper surface loading that is equal to or greater than the lower surface loading, for an approximate cruise lift coefficient (i.e., total normal force coefficient of 0.2) [12]. Also depicted on the plot are lines of constant leading edge sweep angle and lines of constant $\beta\cot\Lambda$ values. These data show that there are a number of Mach number and wing sweep combinations that result in the linear theory assumed split in loading between the upper and lower surface and thus offer the opportunity for low pressure

drag at lifting conditions. The data show that the limiting Mach number for a 75° delta wing is 2.11 (top right corner of shaded region) and the limiting Mach number for a 65° delta wing is 1.8 (top left corner of shaded region). Note that both of these Mach numbers are less than the design Mach number of 2.4 chosen by the HSR program.

On the right side of figure 7 is a plot of the percent of the 100% linear theory leading edge thrust value with lift coefficient for several different flat (no camber or twist) wing geometries. The 100% leading edge thrust value is accepted as the lower boundary that defines the maximum drag reduction potential due to wing camber and twist at supersonic speeds. As a point of reference a typical wing camber and twist design activity would have a goal of 50% to 70% leading edge thrust. The data presented are for nonlinear analysis of two uncambered delta wings (AR = 1.0 and 2.0) and a summary curve labeled as "projected variable camber" that was extracted from existing experimental data [12]. These data show that 100% thrust is achievable for low lift coefficients (less than 0.10) and high levels of leading edge thrust can be achieved for lift coefficients out to 0.30.

### 3.2 Arrow Wings

For more than five decades the arrow wing planform has been considered the preferred planform for efficient supersonic flight. This preference is due to the predicted low drag and increased lifting efficiency derived from the increase in aspect ratio. Unfortunately, neither of these aerodynamic benefits have been realized from any of the various concept development activities. One reason for the failure to achieve the projected aerodynamic benefits of the planform is that it has not received adequate attention in fundamental aerodynamic research studies to properly document the unique aerodynamic characteristics associated with a highly swept trailing edge.

Arrow wings have been studied, to a limited degree, since the inception of supersonic research. The planform has taken many forms as shown in figure 8 and it has also been subjected to various perturbations such as the swing wing concept. Despite the diversity of concepts that have been developed to exploit the aerodynamic advantages of the arrow wing there is little fundamental research directed at addressing the primary limiting factor of the planform, trailing edge separation.

As shown in figure 9 the uncontrolled spanwise flow and resulting trailing edge separation on an arrow wing causes an pitch up of the wing. The oil flow photographs [13] of figure 9 show that the separation is a result of the spanwise flow that develops along the wing trailing edge. This spanwise flow is a product of the trailing edge pressure differential that increases in the spanwise direction for this planform. Arrow wing research into this effect has unsuccessfully focused on wing camber and twist to control the pressure gradients. The issue with the previous efforts is that they employed typical, linear theory based, airfoils that magnify the adverse pressure loading, independent of the twist and camber incorporated into the wing. An alternate design approach would be to shape the wing in a manner that locates the wing maximum thickness at .6 to .8 chord. This proposed shaping has the potential to reduce the adverse pressure loading at the trailing edge. Additional geometric modifications to the typical arrow wing geometries would be the use of forward leading-edge sweep, increased airfoil thickness in the spanwise

direction, and increased leading edge bluntness in the spanwise direction. These modifications would improve the aerodynamic performance of arrow wings have the potential to improve the structural performance of the planform.

## 4.0 Opportunities

Though there has been more than fifty years of supersonic aerodynamic research and vehicle development there has been relatively little advancement in the rules, criteria, and techniques used in the aerodynamic design of supersonic cruise vehicles since the 1960s. Another observation is that there has been limited transfer of aerodynamic knowledge and design experience between the military and commercial sectors of the aerodynamic community. The military community had historically supported a base level of fundamental research in supersonic cruise vehicle design from 1940s to 1990s whereas the commercial sector suffered through many start and stops, as documented previously. The military focused supersonic aerodynamic research benefited from long range goals and a stable funding environment which supported research of both traditional and non-traditional drag reduction technologies. Examples of two such research efforts are the multiple wing [14] and multiple body [15] research efforts as shown in the photographs of figure 10. It is unfortunate that the commercial community has been unable to leverage the military based technologies in the development of a viable commercial supersonic cruise vehicle.

The remainder sections of this paper will discuss a number of aerodynamic pressure drag reduction opportunities that offer the potential for the successful development of a commercial supersonic transport.

### 4.1 Drag Reduction-Interference Effects

There have always been two primary supersonic aerodynamic design philosophies. The dominant design philosophy has been one that optimizes the aerodynamic performance (i.e. drag reduction) of each component of the vehicle and then integrates the components into a single vehicle by minimizing the interference effects between the components. This approach is at times performed explicitly and at times implicitly, depending upon the knowledge level of the designer. If the designer makes extensive use of linear theory methods or design rules the minimization of interference effects is included in the process.

The second design approach is to design the vehicle as an integrated unit in which the drag of the vehicle is minimized through shaping and the orientation of components to take maximum advantage of positive interference effects [15 - 19]. Classic examples of this design approach are the Busemann bi-plane concept and the ring-wing concept. Interference effects should be viewed as unique opportunities that allow a designer to improve the aerodynamic performance of supersonic cruise vehicles. These interference effects can take various forms such as a direct pressure field that either increases or decreases the pressure on the receiving surface. The fields can also be used to modify the local flow angles that impinge upon another surface of the vehicle. The following two sections will discuss examples of each of these two types of interference effects.

### 4.1.1 Body to Body

The opportunity to reduce the pressure drag of a vehicle by using a pressure field generated by one surface to modify the pressures on an opposing surface will be discussed in the context of body-to-body interference. Examples of this technology are represented by the multiple fuselage vehicle concepts, as depicted in figure 11 [15, 17]. The sketches and photographs of figure 11 provide a technology development timeline for supersonic multiple fuselage vehicle concepts [15]. One of the first researchers to investigate the multiple fuselage concept was R. T. Jones who explored the concept in support of his investigations into the oblique wing concept in 1972. This effort was followed by the work of Maglieri in 1980, who studied the concept at the tail end of the SCR program. These efforts were followed by experimental, analytical, and design research by Wood in 1982 [17] on a high fineness ratio vehicle and in 1985 [15] on a low fineness ratio vehicle in which a tri-body configuration was designed and the drag reduction was experimentally verified.

A simplistic explanation of the benefits of multiple fuselages is presented in figure 12 in which the predicted variation in the zero lift pressure drag for a conventional single body vehicle and a multiple body vehicle are plotted as a function of configuration slenderness ratio, at a Mach number of 1.80. The data show that, for all slenderness ratios, the multiple body vehicle has 25-30% lower pressure drag than the single body vehicle. The lower drag is a result of the positive forebody compression pressures emanating from each forebody, of a two body vehicle, and impinging on the rearward facing surface of the aft portion of the adjacent body, thereby increasing the aft body pressure and reducing the drag.

Presented in figure 13 are the results of a multiple body design activity for a military supersonic cruise vehicle. The design Mach number was 1.80 and the design lift coefficient was 0.10. The goal was to redesign the existing single body supersonic cruise vehicle into a multiple body supersonic cruise vehicle that would have a 10% reduction in drag. The multiple body vehicle would have equal or greater fuselage volume, wing volume, and an equivalent vehicle footprint on the ground. It was also decided that the planform characteristics would remain constant for the study.

The design process started with a redistribution of the single body fuselage volume into three bodies, a center fuselage that matched the existing single fuselage forebody area distribution in order to house the pilot and avionics and two side fuselages. The total fuselage volume for the three fuselages was greater than that for the single fuselage. The shape of each fuselage, of the three fuselage concept, were designed to maximize the interference effects between the three bodies. In the design process it was decided that the dominant interference effect to be maximized was the impingement of the compression field, generated by each side fuselage forebody, on the aft portion of the center fuselage. The resulting drag reduction exceeded the 10% goal despite the fact the detailed body shaping activity was performed without the assistance of advanced computational methods.

Another perspective to the benefit of body-to-body interference effects is shown in figure 14. The figure depicts the variation in zero lift pressure drag with Mach number and the pressure drag at lifting conditions with lift coefficient for a conventional transonic based design fighter, a conventional supersonic cruise vehicle, and a

multiple body vehicle of equivalent volume and wing area. These data show that a multiple body vehicle can be designed to provide low levels of pressure drag at both zero lift and at lifting conditions by allowing for the integration of lower sweep and higher aspect ratio wings without incurring the zero lift pressure drag penalty that is observed for conventional designs.

### 4.1.2 Body to Wing

Body-to-wing interference effects can take two forms; 1) interfering pressure fields that are similar to those discussed above in section 4.1.1 or the interference between a nacelle and wing [16] and 2) production of a favorable upwash field that allows the wing to operate in an improved flow environment and a lower angle of attack. The discussion in this section will focus on the latter of these two effects.

The concept of reducing the drag of a vehicle by optimizing the fuselage upwash field that acts on the wing has been known and documented for nearly 50 years [18, 19]. Fuselage upwash is produced when a body is at angle of attack and is carrying lift along its length. When the body is lifting the flow on the surface will expand from the lower surface to the upper surface around the sides of the body. This expanding flow will induce a vertical velocity component of the flow immediately outboard of the surface flow. This flow field is termed the induced flow field. While this flow field decays rapidly in the spanwise direction the local flow angle near the side of body can be very large. The integrated effective upwash that a wing will see can be approximately equal to one half the angle of attack of the body, for body angles of attack less than 5°. The drag reduction benefits for the vehicle are a result of the flat drag bucket for a body as shown in figures 15 [20, 21] and 16 [22] and the reduced angle of attack required for the wing as shown in figure 17 [22], for an equivalent lift coefficient. In addition to the drag reduction benefits afforded by the body upwash field, there may be a reduced trim drag penalty as the body incidence will produce a positive shift in the pitching moment curve. This moment increment can be used to trim a vehicle at cruise lift conditions.

Two examples of the supersonic aerodynamic drag of bodies are presented in figure 15 [20, 21]. The plot on the left of the figure is for an axisymmetric body and the plot on the right show data for seven different cross section shaped bodies. All of the data of figure 15 clearly show the nearly flat bucket (i.e., constant drag level) for body angles of attack between 0° and 5°. This characteristic of body drag at supersonic speeds allows the designer significant flexibility in developing a supersonic cruise vehicle. To take advantage of this design flexibility and the positive interference effect, in the form of fuselage upwash, it is important to understand the lift and pitching moment characteristics of a body, as shown in figures 16 and 17 [22]. The data of figure16 show that the lift and pitching-moment characteristics are linear with angle of attack and that the body contributes less than 10% of the vehicle lift but does produce a significant amount of pitching moment. The data of figure 17 support the observations from figure 16 and also show the large increments in wing lift that result from the fuselage generated upwash field. The oil flow data and lift coefficient data show that a 5° fuselage incidence, relative to the wing, produces an upwash field that allows the wing to achieve the same lift coefficient as the baseline geometry at a 2° lower angle of attack. This change in wing angle of attack will result in drag reductions of 5%.

### 4.2 Wing Drag Reduction

Wing design is a complex process involving all aspects of the subject vehicle, including the fuselage, nacelles, empennage, and the wing itself. To maximize the performance of a vehicle the wing design activity must be continuous throughout the vehicle design process in which planform shape and wing shape are continually modified to account for the changing interference effects and flow environment.

Aerodynamic wing design for efficient supersonic flight continues to be driven by linear theory design rules, guidelines, and criteria. A linear theory design process is based on superposition and is highly sequential. The design activity would start with planform selection, proceed to airfoil selection, and finish with camber and twist design. The assumption is that the benefits from each step are carried, interference free, to the following step. The wing is then fitted to the fuselage to minimize negative interference effects from the fuselage.

Examples of linear theory design rules and/or guidelines are;

1. airfoils are used to define wing thickness
2. airfoils must be less than 5% thick
3. airfoils must have the maximum thickness between .4 and .6 chord
4. airfoils can not have large leading edge radii
5. airfoils must have a sharp trailing edge
6. airfoil definition parameters must remain constant or reduce in the spanwise direction
7. airfoils are applied to the wing in the streamwise direction
8. increasing wing thickness and/or leading edge bluntness will increase the drag
9. reducing wing sweep and/or increasing wing aspect ratio will increase the drag
10. the flow over the wing must be attached

It is interesting to note that existing supersonic aerodynamic data do not support these rules yet they continue to influence supersonic aerodynamic design. Designing a wing in a linear theory framework will result in a wing that has a very benign flow field and loading, representative of a linear theory predicted environment. However, these design studies will typically use a nonlinear computational method to model the linear flow environment and support the design effort.

A review of existing supersonic aerodynamic data for wings show that wing performance can be significantly enhanced by taking full advantage of nonlinear flow phenomena. Specific observations of existing data show that wing design should be aligned with the following criteria;

1. define the three dimensional wing shape to work with the observed (naturally occurring) pressure loading
2. increase the wing volume, wing thickness, and leading edge bluntness in the spanwise direction
3. design the upper and lower surfaces independently
4. design the wing to take advantage of attached or separated flows

To take full advantage of these criteria does not require the use nonlinear computational methods but does require detailed surface modeling tools in order to model the wing surface to work with the naturally occurring pressure loading. While planform selection will start a design activity, the planform design will not stop with the selection.

The following sections of the paper will discuss several examples of planform design and wing surface shape design for reducing the supersonic pressure drag.

### 4.2.1 Multiple Wings

Planform design is critical to achieving efficient supersonic flight and effective off-design performance. A wing planform establishes both the drag reduction potential of the vehicle and the technology concepts that can be employed to improve the aerodynamic performance at off-design conditions. However, a review of the wing design literature shows little variation in planforms selected/designed for supersonic flight, and even less information on the rationale for planform design. With the exception of a few examples the existing data are for conventional single wing concepts of a delta or cranked delta type. The literature show that the extreme perturbations in planform shape have been arrow wings and the skewed wing concept. The lack of diversity in planform selection and planform design represents a missed opportunity.

In an effort to expand the planform data base, a limited investigation was performed on multiple wing concepts [14]. The idea of using multiple wings is based upon the hypothesis that this planform type will allow for increased aspect ratio, increased wing volume, reduced wing sweep, improved body-to-wing and wing-to-body interference effects, and improved longitudinal lift distribution leading to lower pressure drag and lower sonic boom. A sample of the data obtained in this investigation is presented in figure 18 that show the trends in zero lift drag and lift curve slope, with Mach number, for a baseline single wing and the multiple wing concept. Both concepts used the same fuselage geometry that was designed for the single wing planform. In the design of the multiple wing concept the wing volume had to be increased to minimize negative wing/body interference effects with the existing fuselage. A comparison of the results presented in figure 18 show that the baseline single wing concept had a 2% lower zero lift drag value but the multiple wing concept had a lift curve slope that was 15 to 20% greater than the single wing concept. Converting these data into a drag reduction value shows that the multiple wing concept had 2% lower drag at the supersonic cruise point and would have improved performance at transonic and subsonic flight conditions as a result of the increased lift curve slope.

The above example only serves to highlight the potential of the multiple wing concept. Additional planform research is required on multiple wings, arrow wings, and joined wings.

### 4.2.2 Vortex Flow

For decades aerodynamicists have pursued vortex flow as a means to improve the subsonic and transonic aerodynamic performance of thin, sharp leading edge, highly swept wings. These efforts have been motivated by the needs of the various supersonic transport development programs and have produced measurable results. However, the geometric characteristics of a vortex flap design concept would typically conflict with the geometric requirements of the wing leading edge for efficient supersonic cruise.

To explore the possibility of using vortex flows to improve supersonic aerodynamic cruise performance an experimental and computational investigation was performed at NASA Langley in the 1980s [23, 24]. One of the objectives of these studies was to develop a supersonic vortex flap design concept that would be consistent with the vortex flap concepts being developed for subsonic and transonic flight [25, 26]. A summary of the supersonic vortex flap

design efforts is shown in figure 19. The data presented are for a 75°-swept delta wing configured with a conical leading edge flap that comprises the outer 30% of the local span. Vortex flap deflection angles of 0°, 5°, 10° and 15° were investigated for Mach numbers between 1.7 and 2.8. Shown on the right side of the figure are upper surface pressure coefficient data and vapor screen photographic data for the 5° flap deflection geometry at M=1.7, and 6° angle of attack. All of the data obtained in the investigation showed that the flow over the delta wings was conical about the apex of the wing. This characteristic of supersonic flow allows for the complete wing flow and loading to be examined by looking at data for a single fuselage station. The surface pressure and vapor screen data show that the classical vortex flap performance conditions can be achieved at supersonic speeds (i.e. vortex residing on the flap with attached flow inboard). A summary of the data obtained is presented on the left of the figure and shows there is a 3° wide range of angle of attack in which the vortex flap goal is satisfied (i.e. vortex resides on the flap only). The drag reduction achieved for these conditions were significant and varied between 20 and 30 counts for a cruise lift condition of 0.10. These results suggest that the opportunity exists to use vortex flows at all speeds to improve the aerodynamic performance of highly swept, thin, and sharp leading edge wings. Note, the ability to achieve drag reductions with separated flow at supersonic speeds is counter to the basic premise of supersonic design that states that efficient supersonic aerodynamics can only be achieved with attached flow.

### 4.2.3 Natural Flow

Another approach to multi-point wing design is offered by the natural flow wing design concept [27, 28]. The design concept grew out of an extensive review of the wing design philosophies for subsonic, transonic, and supersonic flight that revealed several contradictions as well as several similarities. The contradictions existed mainly between the subsonic / transonic cruise design philosophies and supersonic cruise design philosophies. For subsonic and transonic designs the tendency is to use a low sweep wing, thick airfoils, and blunt leading edges; advanced supercritical airfoils are most commonly used. Whereas, supersonic designs typically employ wings having higher sweep with thin airfoils and sharp leading edges. At maneuvering conditions all designs employ variable camber devices. The natural flow design concept is a multi-point design concept that shapes the wing upper and lower surfaces independent of one another in order to take maximum advantage of the naturally occurring flow field and pressure loading. The approach is analogous to the philosophy employed in low-speed two-dimensional airfoil design, but it is counter to existing 3-D wing camber and twist design.

A review of the experimental data base for wings showed that the flow and pressure loading on a swept wing in subsonic, transonic and supersonic flow is conical about the wing apex. The conical flow behavior was observed for all wings, independent of thickness and camber. However, the traditional application of thickness to wings (i.e. airfoils defined streamwise) produces a geometry that is conical about the wing tip. The combination of the conical nature of the pressure loading on the wing upper surface and a geometry that is conical about the wing tip results in high and low drag regions on the wing. A graphical depiction of these observations is shown on the left side of figure 20. This graphic shows that for a

traditional wing regions “A” and “C” have high drag and conversely regions “B” and “D” have low drag. The basic objective of a natural flow design activity is to reduce the size of high drag regions and increase the size of low drag regions through 3-D shaping of the wing upper and lower surfaces. A graphical depiction of a natural flow wing is shown on the right of figure 20. The sketch of the wing upper surface shows that the airfoil maximum thickness line was moved forward at the wing root and then swept aft of the expansion region on the wing. These changes reduce the size of region “A” and eliminates region “C”. The lower surface of the natural flow wing has the maximum thickness line moved very near the leading edge to reduce the size of region “A”.

The natural flow wing design concept was applied to the design of a 65° delta wing [27], as shown in figure 21, and was used in the HSR program to improve the performance of a numerically optimized arrow wing [28]. Presented on the right side of figure 21 is a sketch showing elevation cuts through the natural flow designed wing, an intermediate designed wing (near-conical), and a traditional baseline wing. Also shown in the figure are the lifting characteristics and lift-to-drag ratio of the three wings. The geometric information show that both the baseline flat wing and the near conical wing are symmetric geometries. The primary difference is the near conical wing has a thickness distribution that is nearly conical about the wing apex and the baseline wing is conical about the wing tip. The natural flow design has been reshaped to distribute the thickness in a conical fashion about the apex and has a dramatic increase in leading edge bluntness and a relatively flat upper surface aft of the maximum thickness line. The lower surface of the natural flow wing is fully reflexed providing an aft facing surface for the positive pressure to act upon. These geometric characteristics were created by redistributing the wing volume both vertically, laterally, and longitudinally, increasing wing thickness, increasing wing leading edge bluntness, and shaping the upper and lower surfaces independently. The resulting aerodynamic performance increase was greater than 15% for all lift coefficients above 0.05.

It is interesting to note that the uncambered near conical wing provided significant drag reductions that resulted in a 5% improvement in L/D over the complete lift range tested. These drag reductions were achieved by a lateral and longitudinal redistribution of wing volume, an increase in wing thickness, and an increase in wing leading edge bluntness.

The natural flow design concept has also been successfully applied to bodies and full configurations at both subsonic and transonic speeds.

### 4.3 Control Effectors

If future supersonic cruise vehicles are to be viable there must be significant gains in aerodynamic performance at all speeds as well as a reduction in weight and complexity. A means to contribute to these objectives is through the use of advanced aerodynamic control effectors. A review of the history of supersonic aircraft design reveals that aerodynamic control effector technology has changed little since the early 1900's [14]. Aircraft have tended to utilize "typical" suites of moving surface control effectors such as rudders, elevators, flaps, ailerons, etc. The traditional devices create control forces by moving a portion of the

vehicle into the flow passing over the vehicle that produces a change in lift and an increase in drag. The development of the next generation of supersonic cruise vehicles should employ advanced control effectors that have reduced weight and maintainability issues while offering improvements in aerodynamic efficiency. The authors recognize that these advanced control effectors require additional studies in systems, weight, maintainability, etc.

Several example concepts that have the potential to meet these constraints are presented in figure 22. Figure 22 shows two pneumatic devices as represented by passive porosity for direct pressure load control and active blowing for boundary layer control. Also shown are three small mechanical devices; separation control plates that control/promote trailing edge separation, micro-drag generators which use drag as the controlling force, and adapting surfaces for variable camber control.

The following two sections will focus on two types of advanced control effectors; passive porosity [14,29, 30, 31, 32, 35] and small, simple mechanical devices that are located on the upper surface of the vehicle [14, 32]. Although the data for these devices is limited to subsonic Mach numbers, these devices are presented and discussed as examples of viable future control effectors that should be investigated for supersonic cruise vehicles.

#### 4.3.1 Passive Porosity

The passive porosity technology has been extensively studied both experimentally and computationally as a means to control shock/boundary layer interaction, see right side of figure 23 [29 - 33]. The focus of passive porosity research as applied to control effectors was for both local boundary layer management and global application of passive porosity on an aerodynamic vehicle to control the forces and moments of the vehicle. Passive porosity is designed to modify and control the pressure loading acting on a surface The passive porosity concept consists of a porous outer surface and a solid inner surface. The volume between the outer and inner surfaces form an open plenum that is filled with the same fluid which is flowing over the exterior surface of the porous skin. The effectiveness of the concept is dependent upon the ability of the system to allow unrestricted communication between large pressure differences on the external surface (high permeability).

Representative passive porosity control effector results at a Mach number of 0.17 for the 65° Delta wing model are presented in the left side of figure 23. Also shown in figure 23 are representative control effectiveness data for the F/A-18 aircraft at M=0.17 [14]. Roll control for various extents of tip porosity is shown in figure 23. The data are for configurations with porosity applied to both the upper and lower surface. This application of porosity allows the passive porosity system to eliminate (dump) lift on a particular region of a wing. The data of figures 23 clearly show that significant control authority is available with this technology, at moderate angles-of-attack. A comparison of the passive porosity results with those for the conventional aerodynamic control effector show that the passive porosity device is more effective for angles-of-attack greater than 10°.

The failure of the passive porosity device to generate control forces at low lift is due to the symmetric loading on the airfoil at these conditions. As mentioned previously, passive porosity effectiveness is a function of the pressure differential on the surfaces. This observation supports the need to view the planform and surface contour as important contributors to control effectiveness. To maximize the effectiveness of the passive porosity control effector, large pressure gradients must exist on the surface of the vehicle. To create the optimum environment for these effectors may require new families of planforms and surface contours.

Figure 24 presents side force data for a porous 5.0 caliber, tangent-ogive forebody model with various circumferential extents of porosity, a porous forebody with chine, and the F/A-18 HARV with actuated strakes [14]. Also shown on the figure is the available side force from the F/A-18 vertical tail. Slender bodies at moderate to high angles of attack typically exhibit asymmetrical loading conditions. In the region where asymmetric vortex shedding and the resultant side force typically occurs ($\alpha > 20°$), the application of 360° of porosity eliminates the asymmetric vortex induced loading. Application of porosity to the left side of the forebody allows for maximum control of the subject side force. The addition of a chine to the same model increases the magnitude of the side force control generated by passive porosity. As observed with the wing data shown in figure 23, a comparison of the passive porosity generated forebody forces shows significant increases at angles-of-attack greater than 25° over that available with more traditional movable control effectors, a vertical tail, or actuated forebody strakes.

### 4.3.2 Upper Surface Mechanical Devices

Future mechanical effectors will likely be structurally light and therefore may be relatively fragile. A means to protect these effectors from damage would be locate these devices on the upper surface of the vehicle away from FOD. Another reason for locating the devices on the upper surface is that it is a region of the vehicle in which the flow and resultant loading is very sensitive to small geometric changes. This allows for the generation of large aerodynamic effects with minimal mechanical input.

Four examples of small, simple mechanical devices that would be located on the upper surface of the vehicle are shown in figure 25 [14, 34 - 37]. These four devices represent four separate decades of research and are only a very small fraction of the available concepts that should be considered for future vehicle.

The self-activating spoiler concept shown in the upper left of figure 25 is a passive device that is activated and deployed by the pressure differential induced by trailing edge separation [36]. This concept may also be an active device to promote separation on the wing upper surface. This device would benefit arrow wing planforms at supersonic speeds by inhibiting trailing edge separation and it would help all planforms at low-speed high lift conditions consistent with take-off and landing. The oscillating spoiler concept shown on the upper right of figure 25 offers the same benefits as the self-activating spoiler but it does require energy input and would require greater internal volume than the passive system [34].

Shown on the lower left of figure 25 are vertical flaps applied to a delta wing planform [35]. These devices are small in size, less than 5% of the local span, and

work with the leading edge vortex structure to reduce drag. It is envisioned that this device could also be self-activating. The devices are placed under a primary wing leading edge vortex and trip the outward directed flow under the primary vortex to form and control a secondary vortex. This secondary vortex will then induce a suction pressure on the forward facing surface of the device to reduce the drag. The benefit of this device over traditional vortex flaps is that it does not weaken the primary vortex and thus does not reduce the lifting efficiency of the wing. The device can be deployed asymmetrically, in both a lateral and longitudinal sense, to generate control forces without degrading the lifting efficiency or increasing drag.

The last concept to be discussed is the micro-drag generator concept [37]. This device is shown in the lower right corner of figure 25. The micro drag generator concept uses small deployable devices that individually generate small amounts of drag, but when deployed in large numbers can generate substantial amounts of drag. The micro-drag generators may be thought of as miniature spoilers or speed brakes. During normal operation of the vehicle (e.g., during cruise), the devices would not be extended into the flowfield and would not increase the drag of the vehicle. These devices are designed to force the flow on a vehicle to separate on the aft-facing side of the device and to reattach before reaching the next device. The experimental data show that these devices can increase the drag by as much as 400%. If the devices were deployed asymmetrically the magnitude of this asymmetric force is equivalent to the side force generated by the F/A-18 actuated forebody strakes shown in figure 24. These results indicate that by asymmetrically deploying MDGs (only on one wing panel) to an aircraft substantial amounts of control effectiveness (both rolling- and yawing-moment coefficients) may be generated. Therefore, MDGs appear to be an effective concept for decelerating or controlling a vehicle.

### 4.4 Design Approach

The final opportunity to be discussed is that associated with changing the design environment in which aircraft are developed. A review of the literature on design shows a wide diversity of methods, concepts, and ideas being investigated and developed. In general, these concepts fall into two groups, those that are Computationally-Based (CB) Design such as Multi-Disciplinary Optimization and those that are Knowledge-Based (KB) Design. The primary assumption of CB Design is that a design process can be modeled in the computer to allow the computer to find the optimum design more efficiently than a human. Another assumption of a CB Design system is that only explicit and critical knowledge are required to be successful The systems do not recognize the role of tacit and intuitive knowledge and other human senses and capabilities in the design process. At the other end of the design environment are KB Design systems in which it is recognized that all knowledge as well as passion is required to find the best design. KB Design systems consist of tools that allow a designer to utilize their skills, senses, and knowledge in pursuit of a desired outcome.

A review of the aircraft design environment shows that the ability to perform efficient and effective aerodynamic and multidisciplinary design is quickly becoming a lost skill. A significant portion of this problem has resulted from the increased reliance by the aeronautics community upon computational tools for both aerodynamic analysis and design.

This trend towards Computational Based (CB) design and decision making also dominates the multi-disciplinary design environment. As this trend continues, the knowledge and skills, which are the critical elements in the design practices, will slowly erode as the computational tools replace the need for human interaction.

A graphical depiction of the impact of knowledge and design process is shown in the design-development time line of figure 26 [38, 39]. The figure shows that for a traditional design activity the opportunity to impact performance or cost of an aircraft design are heavily weighted toward the conceptual design phase where the design activity is typically guided by first order effects and simple models. However, as discussed above only a fraction of the available knowledge for a particular design problem is associated with these methods and models. This inverse relationship between knowledge used and design impact must be corrected if significant improvements are to be achieved. To improve the design process it is strongly suggested that the traditional design process not be upgraded with the latest computational tools but be replaced with knowledge based systems that account for nonlinear effects using best practice models. The expectation for the change would be a dramatic improvement in vehicle performance and cost for vehicle development.

The second element of the design environment that must be changed is the design team work environment as shown in figure 27 [38, 39]. As depicted in figure 27, there are three types of teams that are possible; Bureaucratic, Hierarchical, and Creative. The Bureaucratic team is formed by the organization and exists as an element of the organization. This team type is recognized as being in competition with other elements of the organization and must operate within the organizational policies and culture. The Hierarchical team is formed by the participating elements of the organization to perform a task of mutual benefit. This team is supported as long as it is recognized as adding value to the individual elements of the organization. Those who have a shared passion and are committed to achieving success form the Creative team. The Creative team operates within the organization environment but performs for the team and the organization. The preferred team is the Creative team, however, it is not one that is typically supported by an organization. The characteristics of a Creative team are increased communications, productivity, and reduced complexity and cost compared to the other two teams.

## 5.0 Concluding Remarks

A discussion of a diverse set of aerodynamic opportunities to improve the aerodynamic performance of future supersonic aircraft has been presented and discussed. These ideas are offered to the community in a hope that future supersonic vehicle development activities will not be hindered by past efforts.

A review of the historically significant supersonic technology programs was presented that showed that the major programs since 1960 have had similar challenges, goals, and as expected have produced similar results. The authors have argued that the success of these programs has limited due to the influence of 1960 based linear theory supersonic aircraft design rules.

To assist the community a number of nonlinear flow based drag reduction technologies are presented and discussed. The subject technologies related to the areas

of interference flows, vehicle concepts, vortex flows, wing design, advanced control effectors, and planform design. Selected specific examples were the multiple body and multiple wing aircraft concepts, passive porosity control effectors, natural flow wing design, and the supersonic vortex flap wing design concept. The authors also discussed the importance of improving the aerodynamic design environment to allow creativity and knowledge greater influence.

A review of the data presented and discussed show that pressure drag reductions on the order of 50 to 60 counts are achievable, compared to a conventional supersonic cruise vehicle, with the application of the discussed technologies. This drag reduction would correlate to a 30 to 40% increase in cruise L/D for a commercial supersonic transport.

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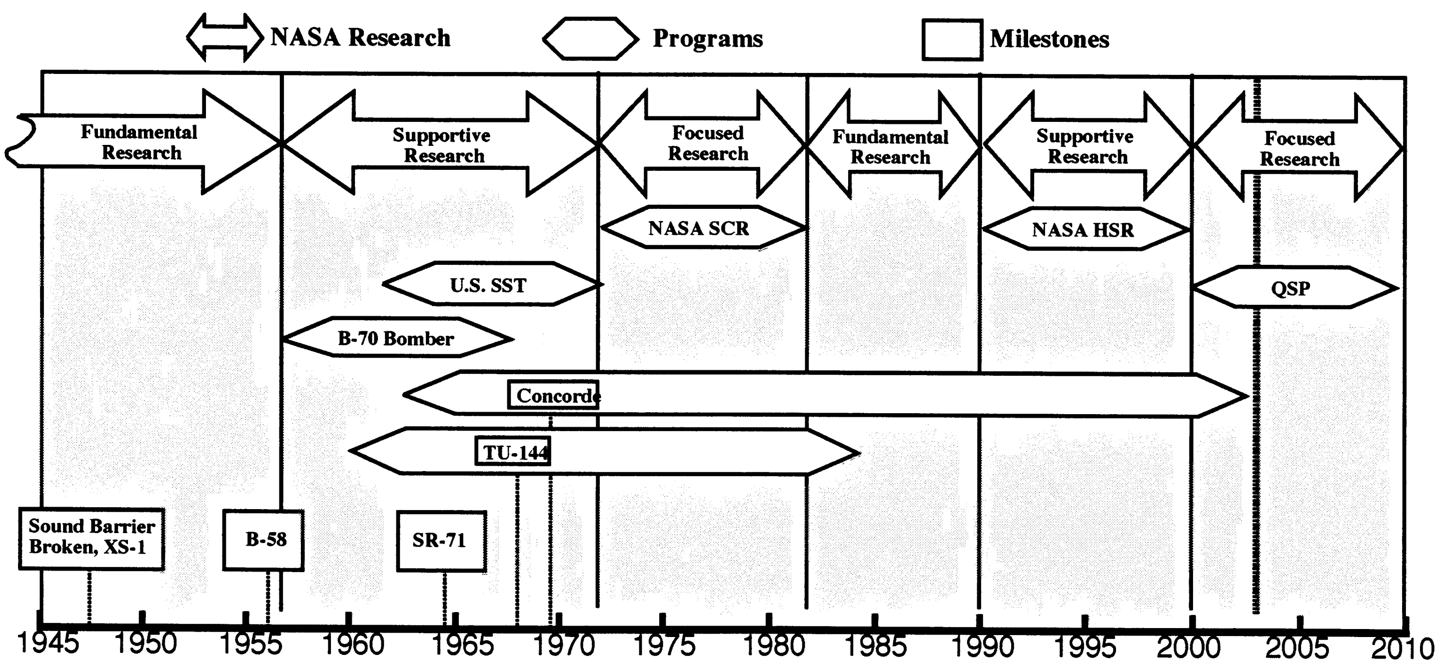



Figure 1. Timeline of significant supersonic aerodynamic development.

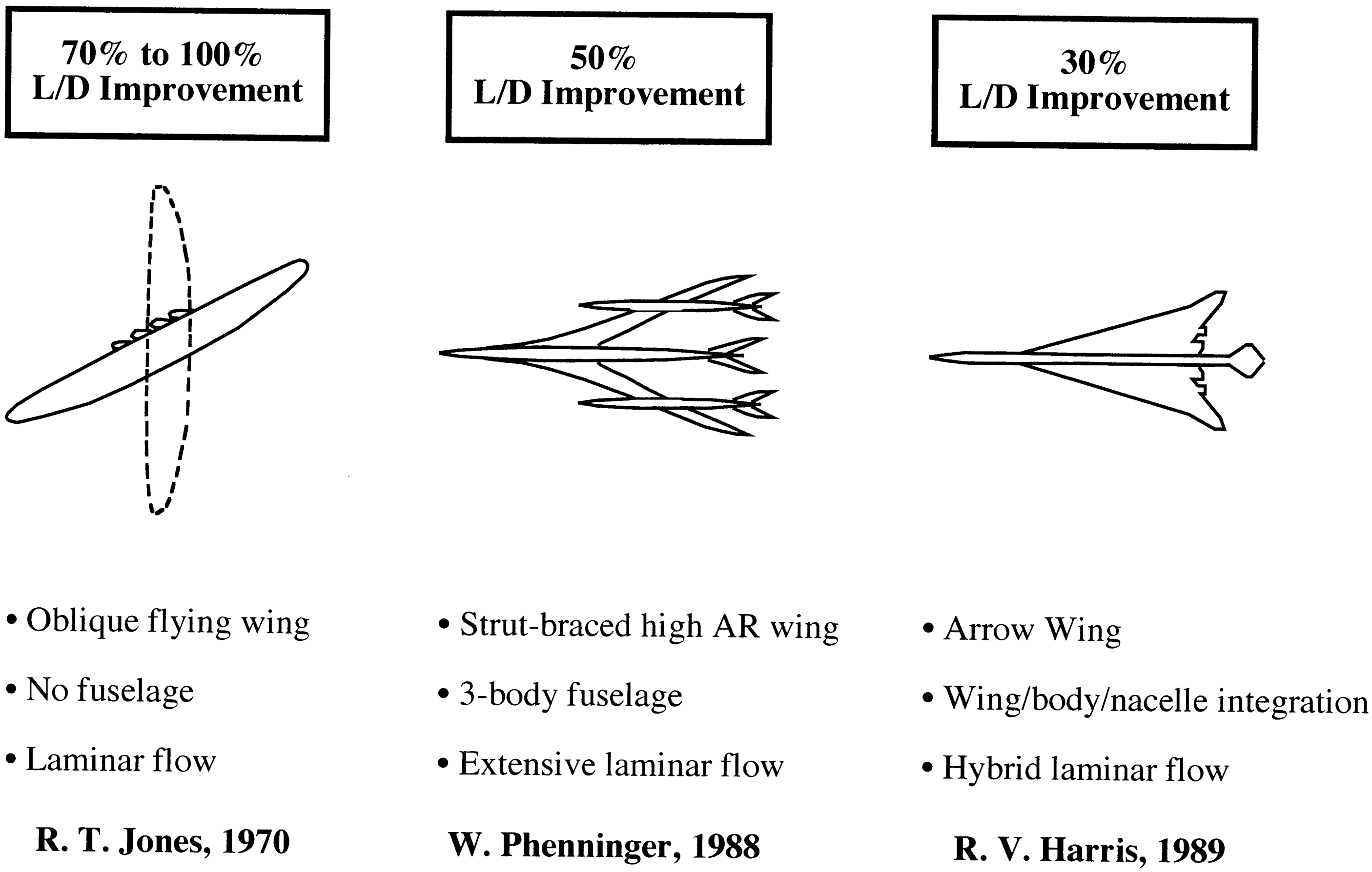



Figure 2. Historical review of projected maximum aerodynamic performance.

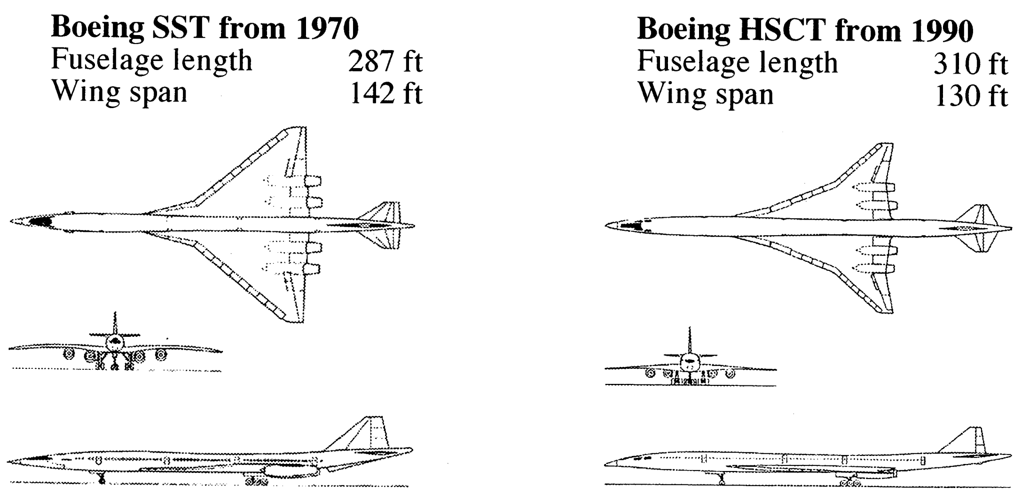



Figure 3. Sketch of 1970 and 1990 target vehicle concepts in the United States supersonic commercial transport development programs.

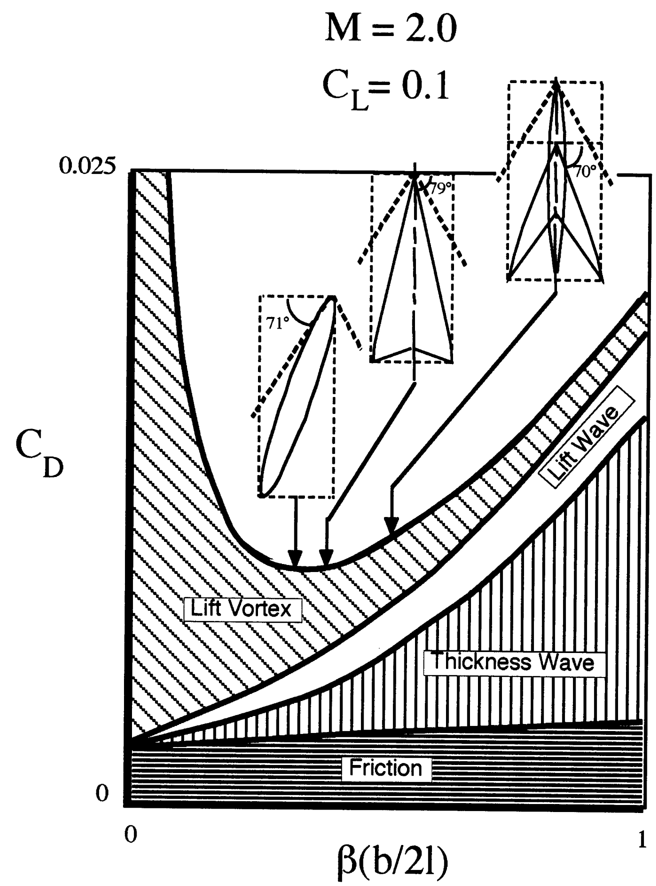



Figure 4. Characterization of the supersonic aerodynamic drag elements based upon linear and slender body theory

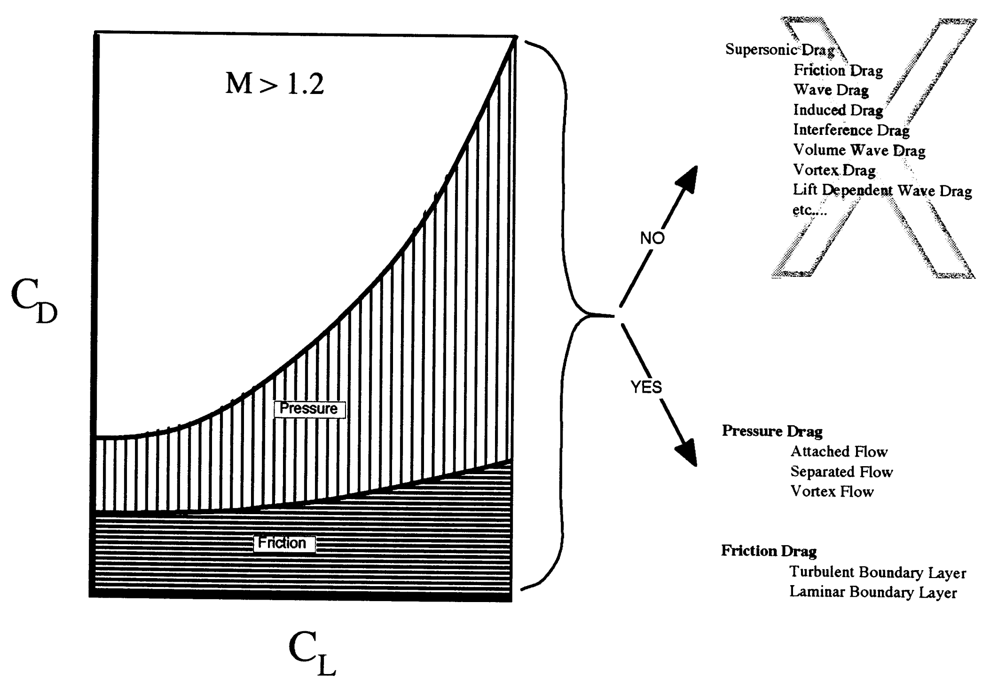
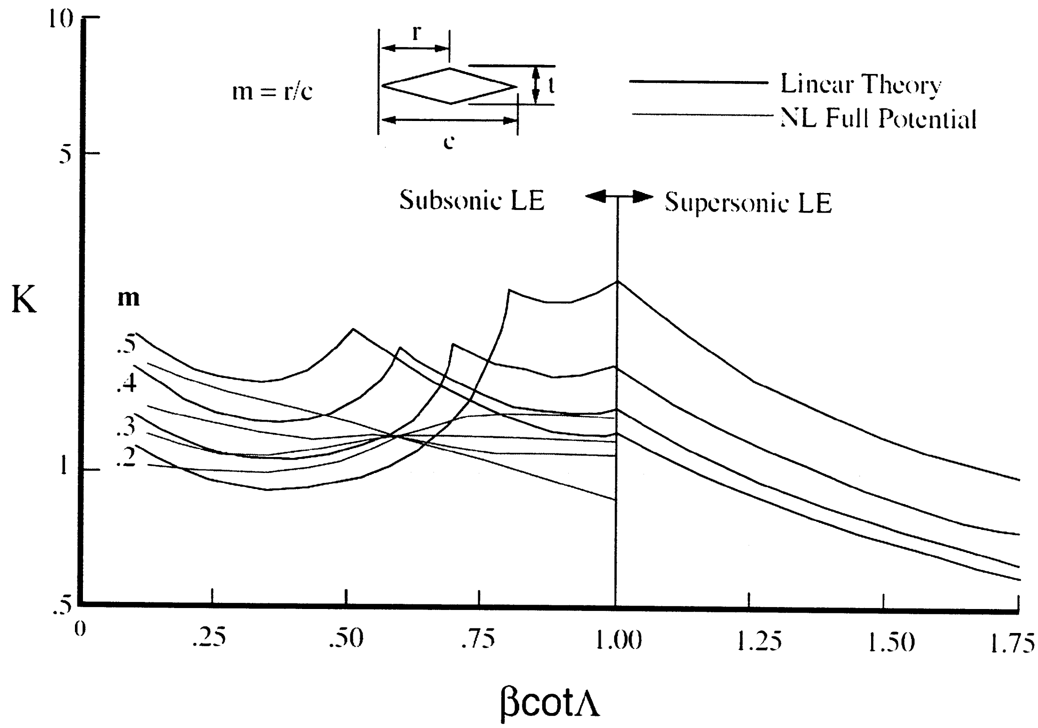



Figure 5. Characterization of the supersonic aerodynamic drag elements based upon nonlinear theory.



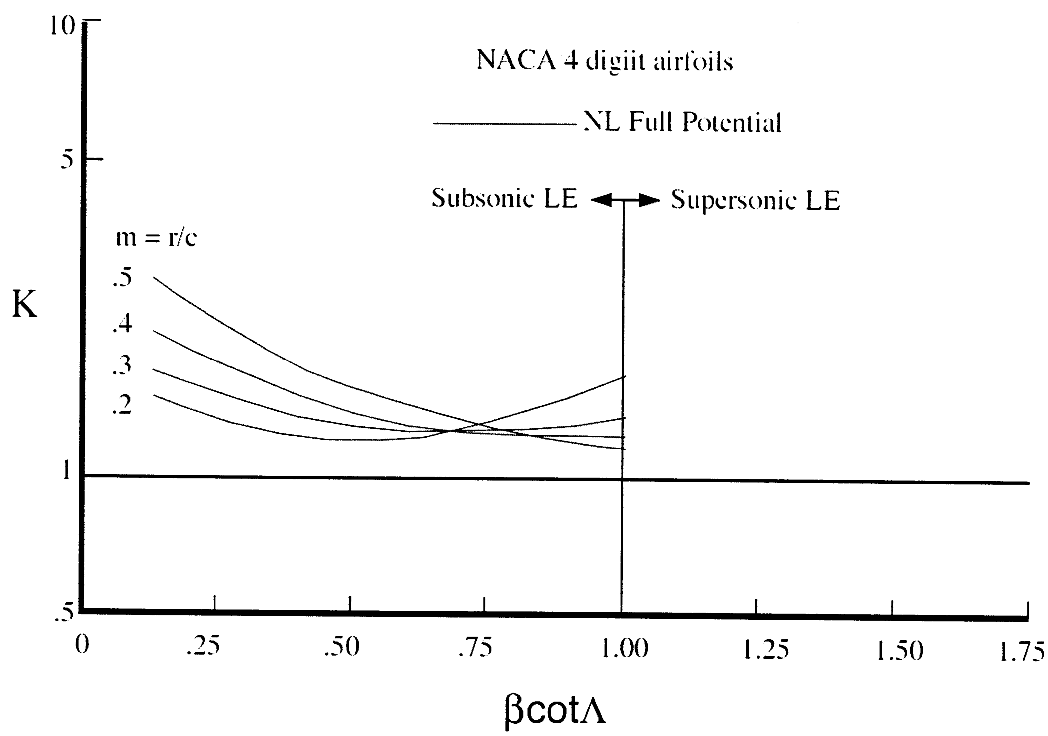
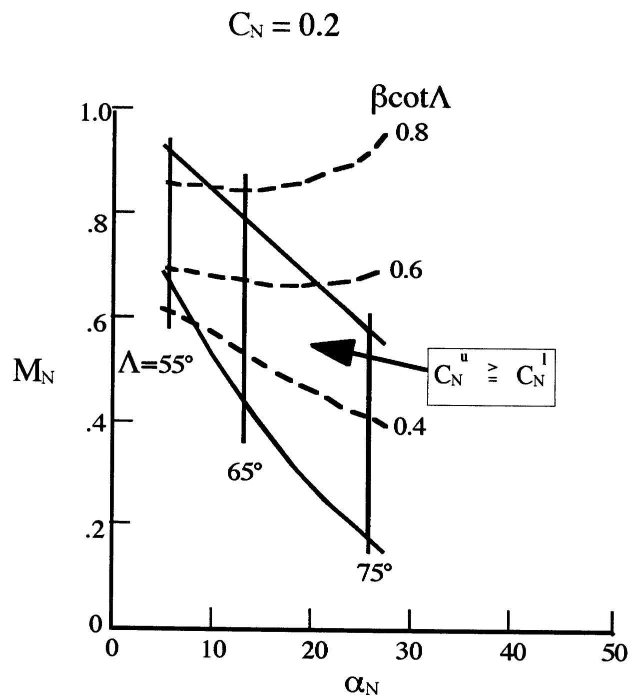




Figure 6. Variation in zero lift pressure drag of symmetric delta wings at supersonic speeds.



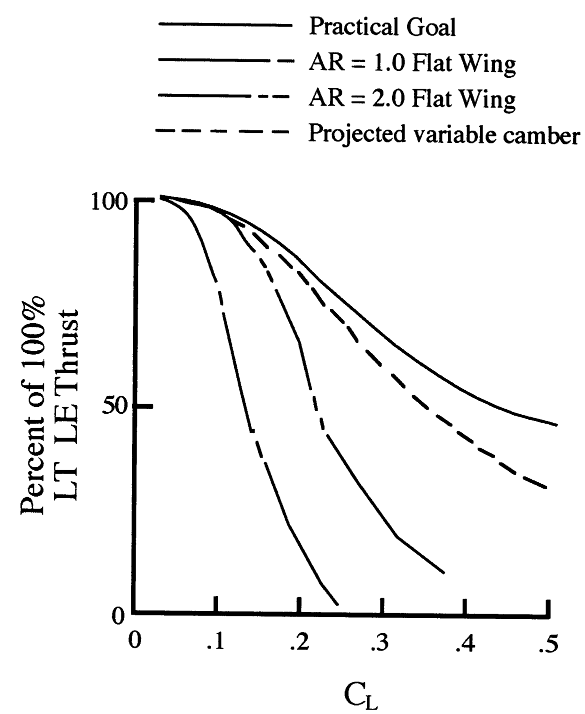




Figure 7. Aerodynamic lifting performance of wings at supersonic speeds.

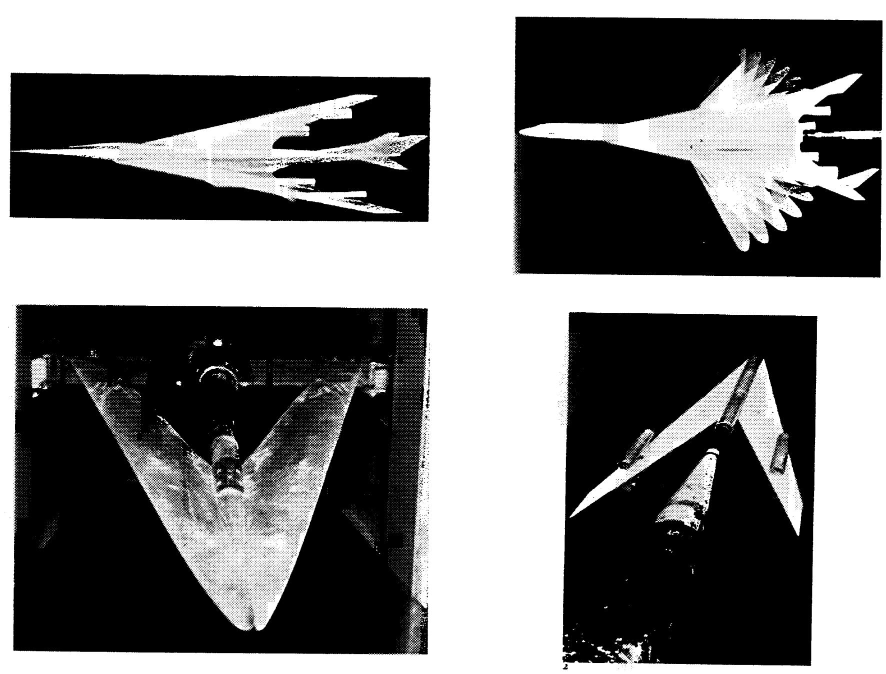


Figure 8. Photographs of various arrow wing concepts investigated at supersonic speeds from 1960 to 1980.

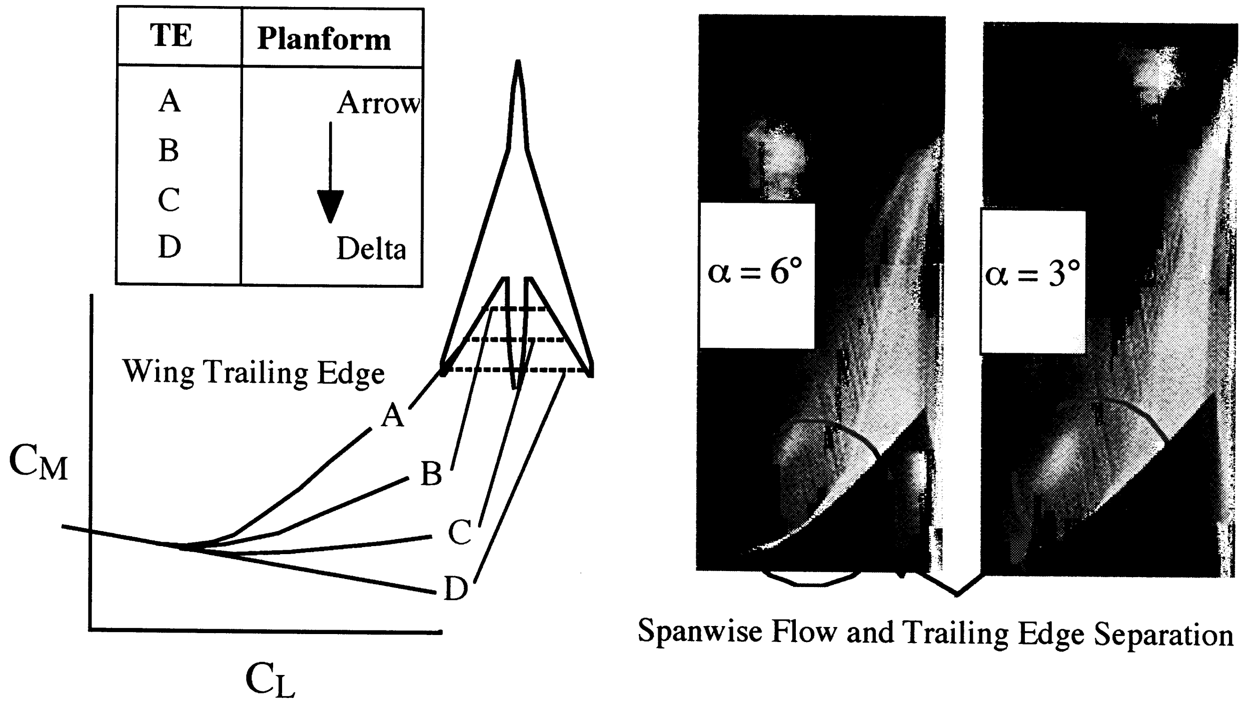



Figure 9. Details of the typical arrow wing pitch up problem.

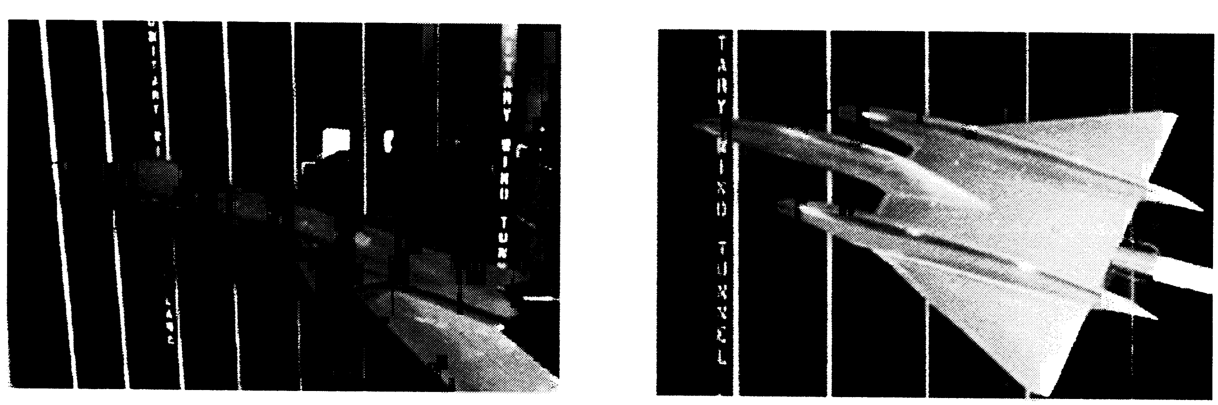


Figure 10. Photographs of two advanced supersonic aircraft concepts investigated at NASA Langley in the 1980s and 1990s.

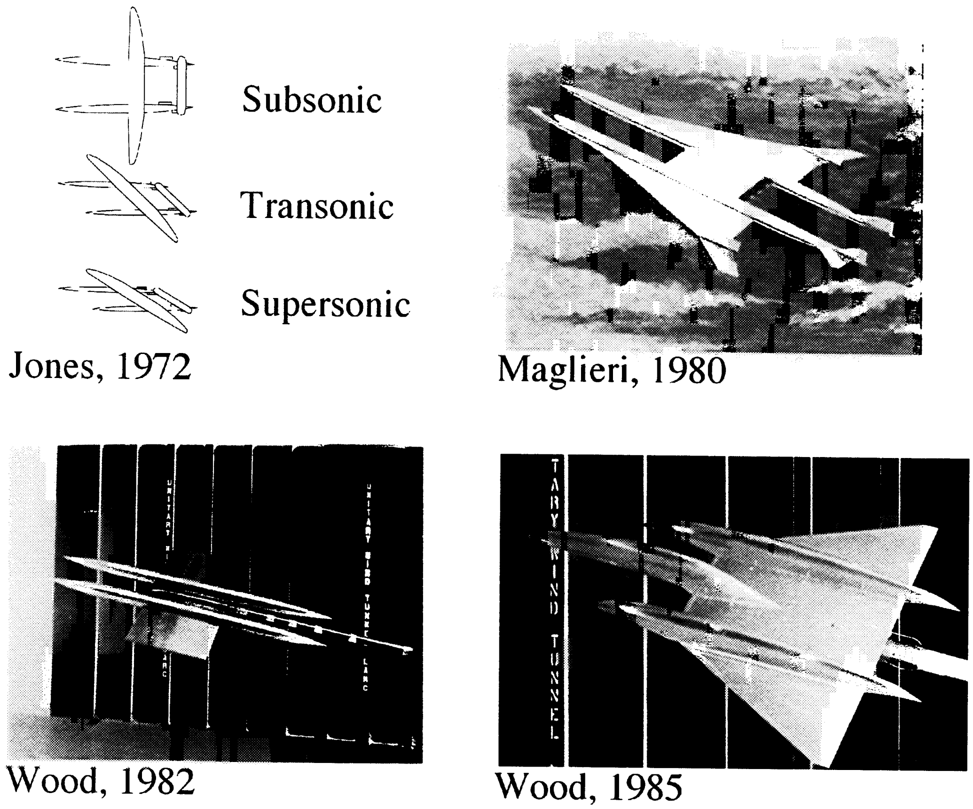



Figure 11. Graphic depicting various supersonic multiple body research studies.

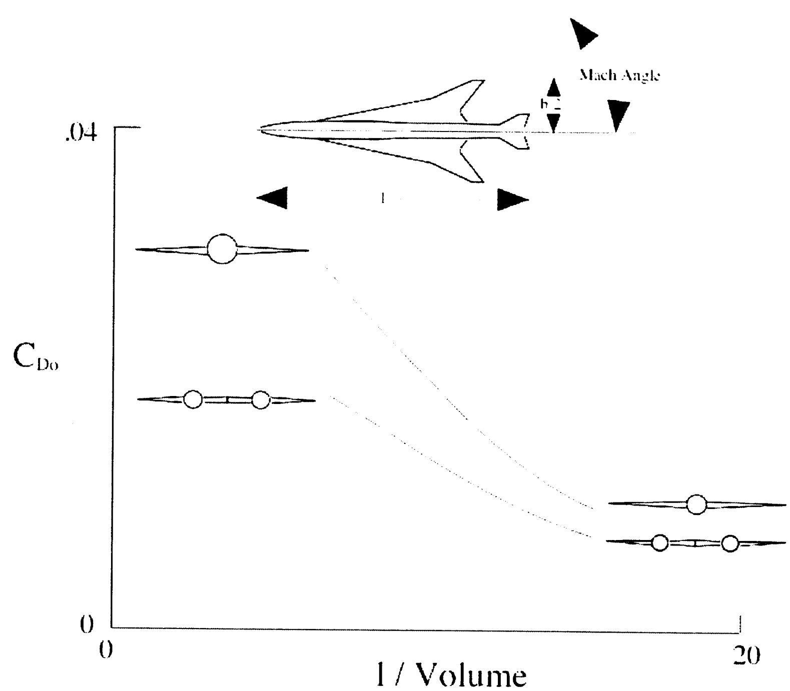



Figure 12. Graphic depicting the variation in supersonic drag reduction potential with vehicle fineness ratio for the multiple body concept.

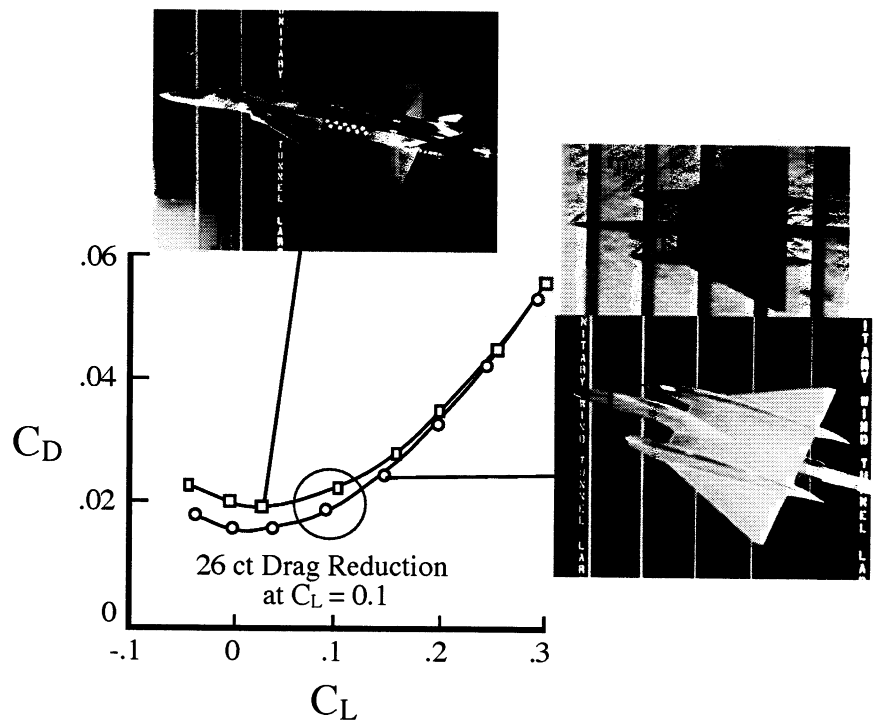



Figure13. Results of a supersonic aircraft concept multiple body design activity

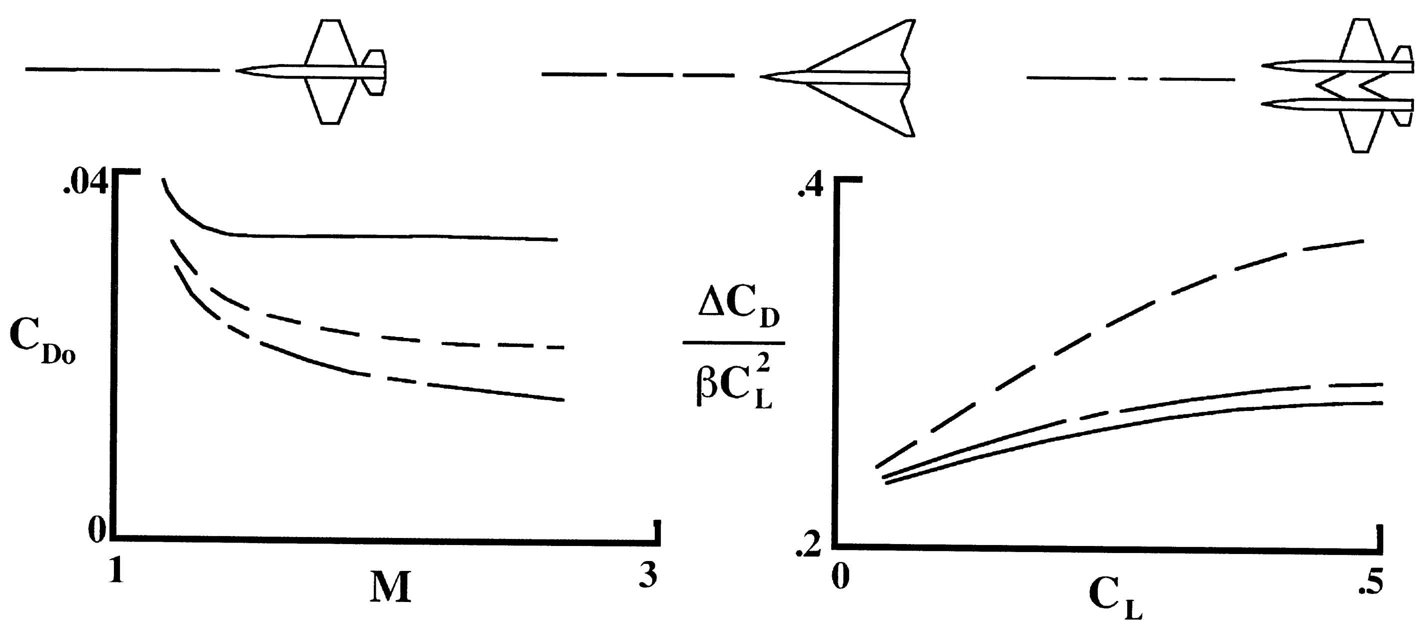



Figure 14. Graphic depicting the variation in supersonic drag reduction with vehicle planform for the multiple body concept.

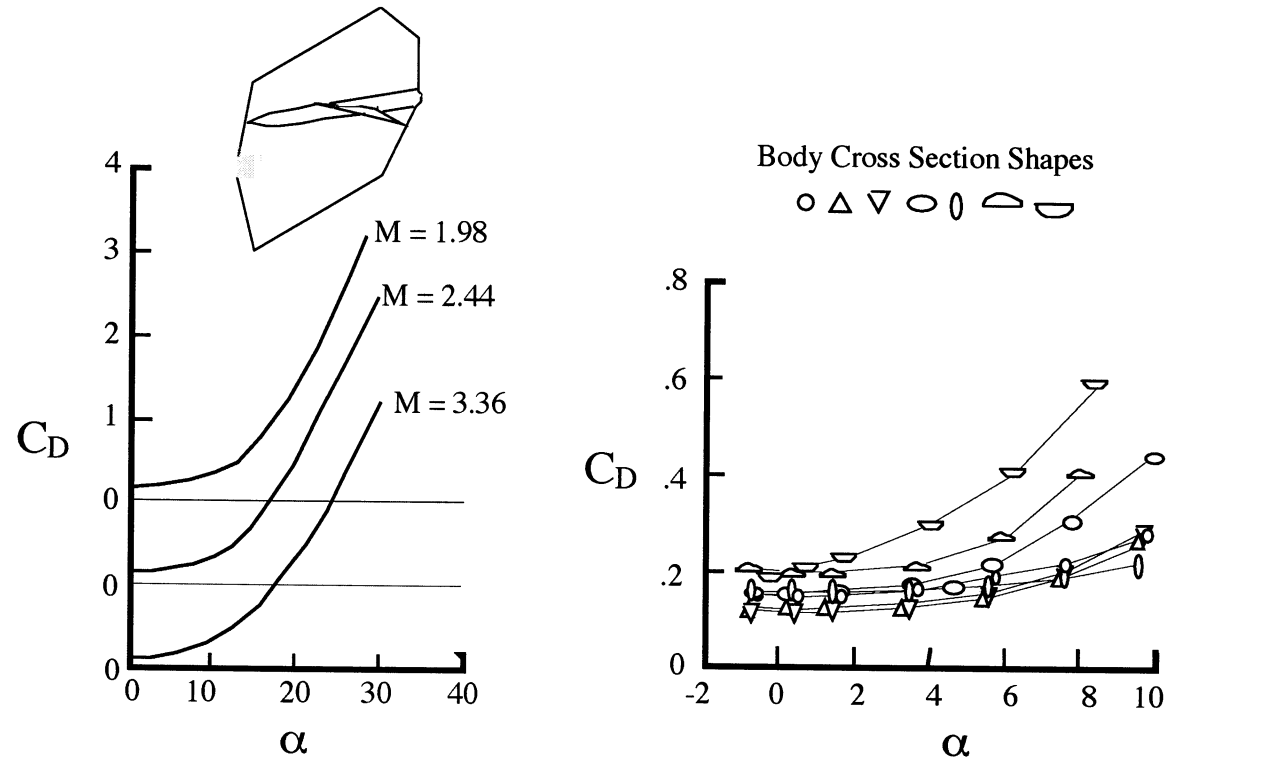



Figure 15. Variation is the drag of a body alone due to changes in angle of attack, Mach number, and body cross section shape.

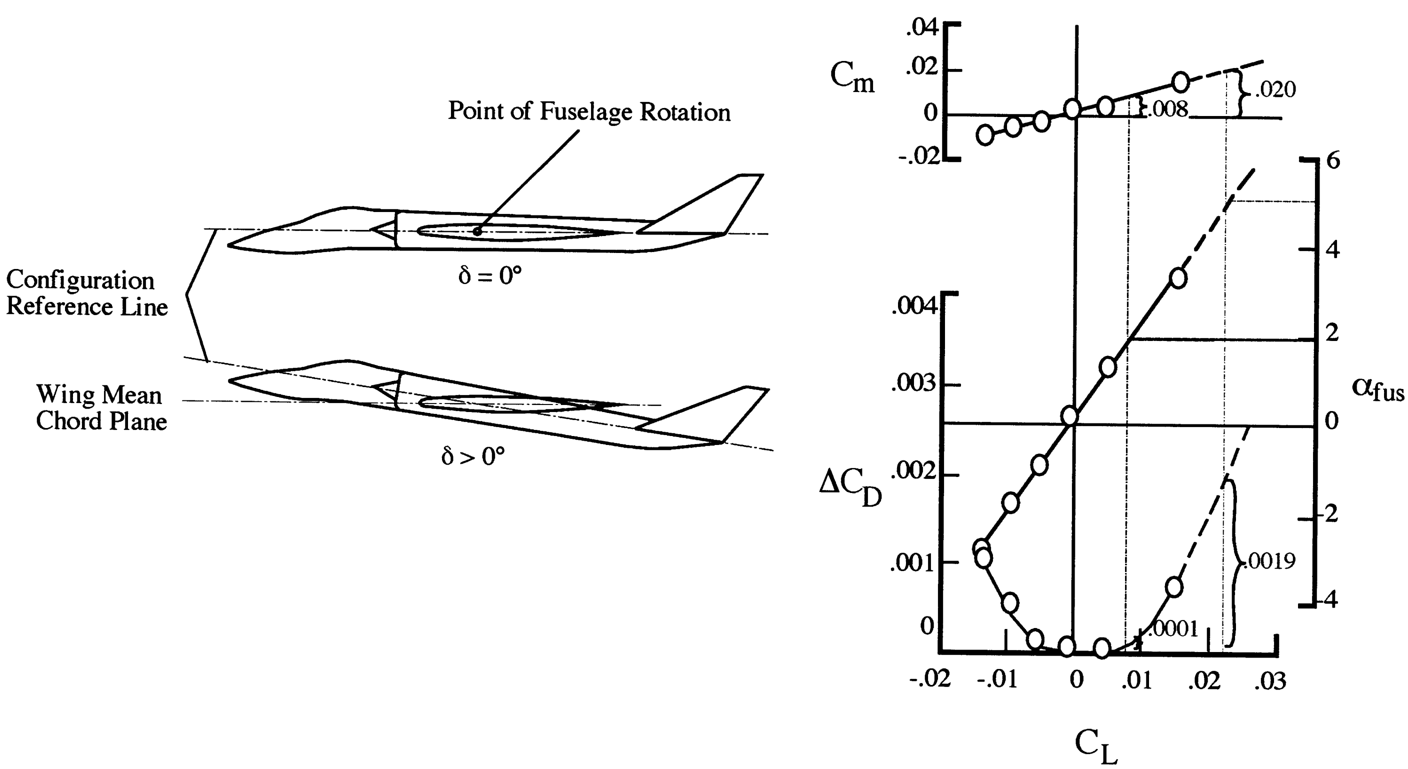



Figure 16. Body alone aerodynamic characteristics for a representative fighter aircraft concept at M= 1.80.

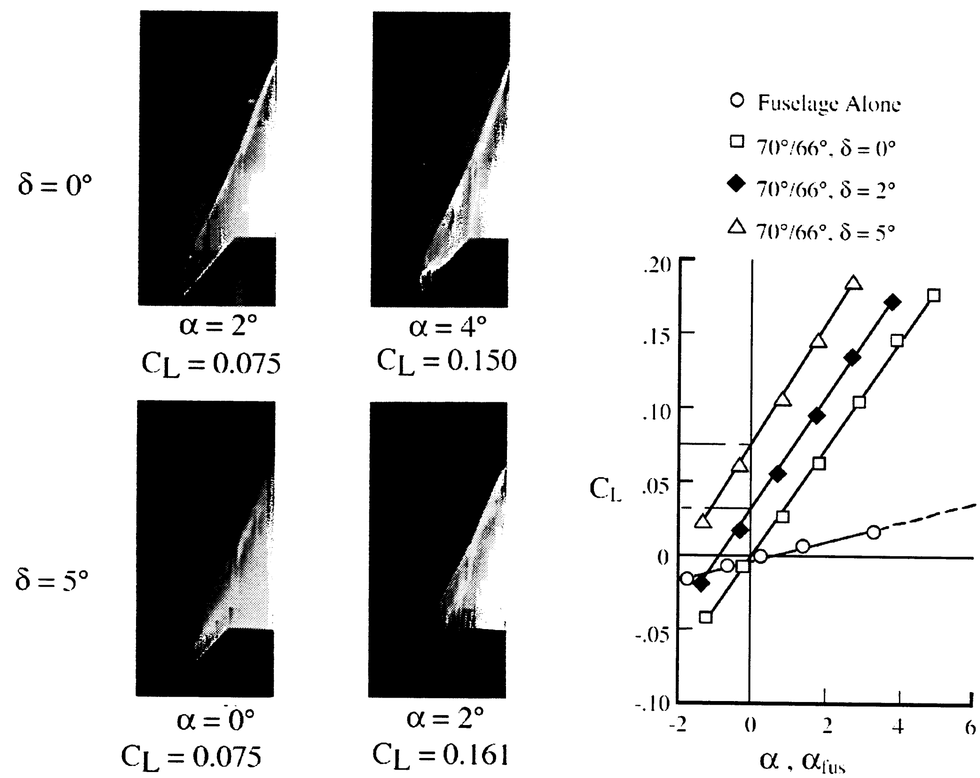



Figure 17. Lifting characteristics and wing surface oil flow patterns for fuselage incidence angles of 2° and 5° at M=1.80

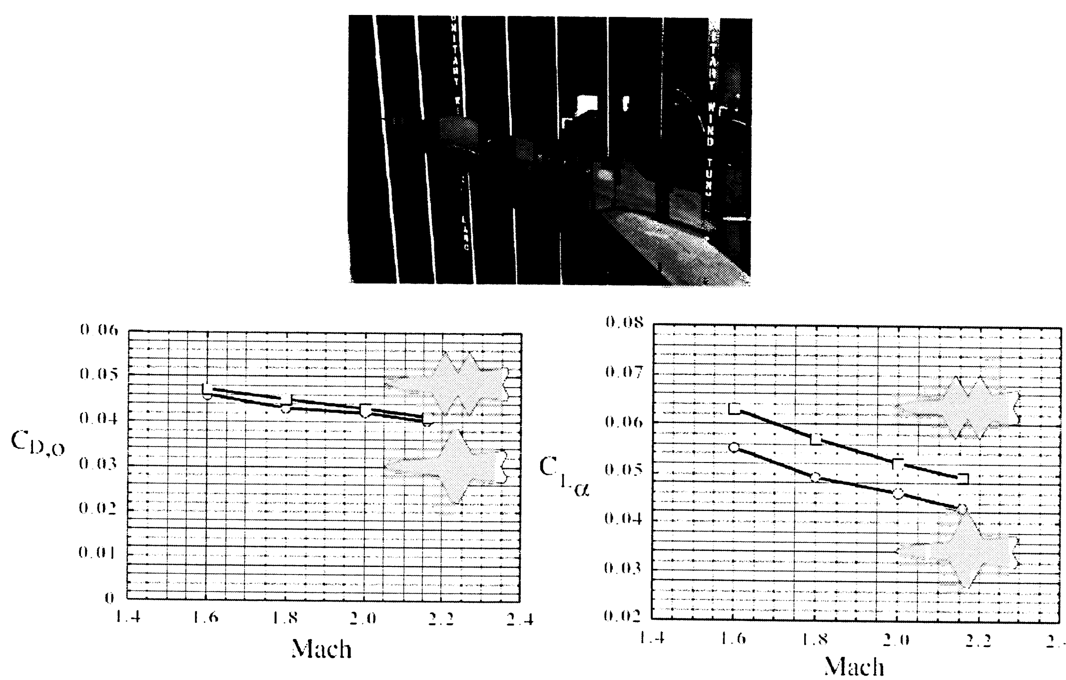



Figure 18. Variation in supersonic zero lift drag and lift curve slope with Mach number for a conventional and multiple wing configuration.

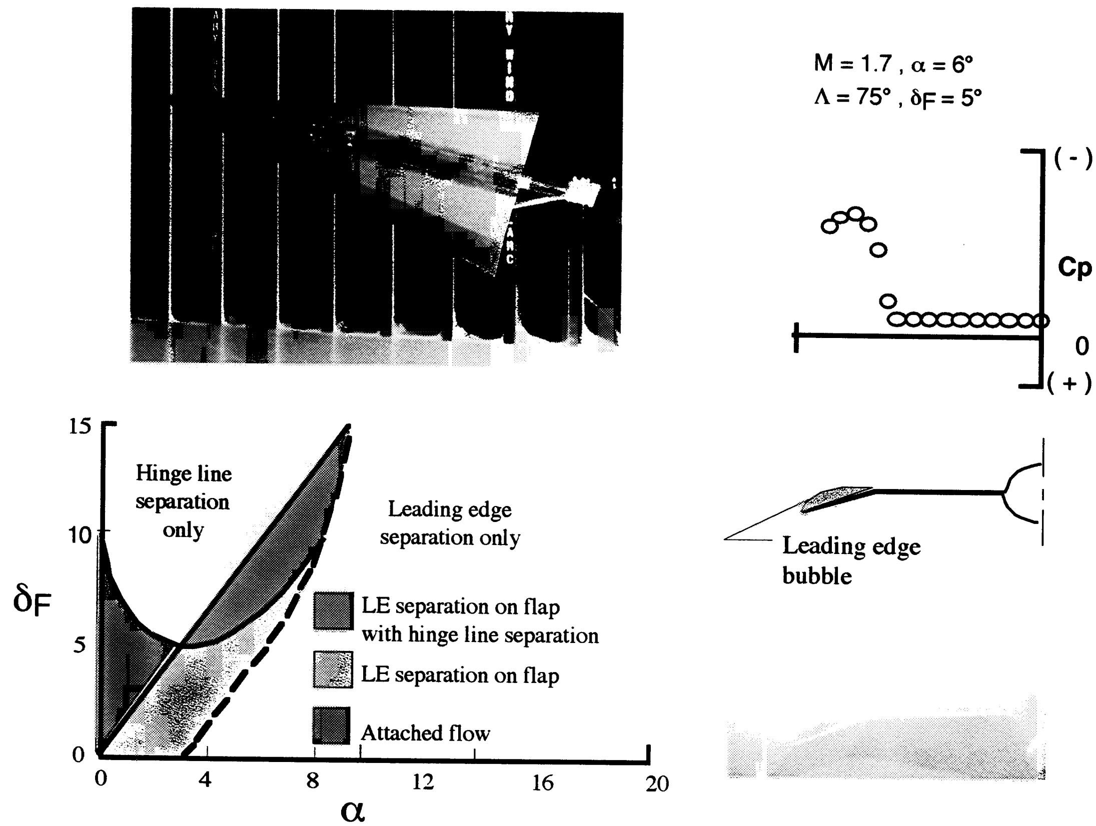



Figure 19. Supersonic vortex flap aerodynamic performance and design information.

| Region | Geometry | Pressure | Drag |
|---|---|---|---|
| A | Positive Slope | high | high |
| B | Positive Slope | low | low |
| C | Negative Slope | low | high |
| D | Negative Slope | high | low |

Expansion Region
Compression Region
Airfoil Maximum Thickness Line
Cross-flow Recompression Line

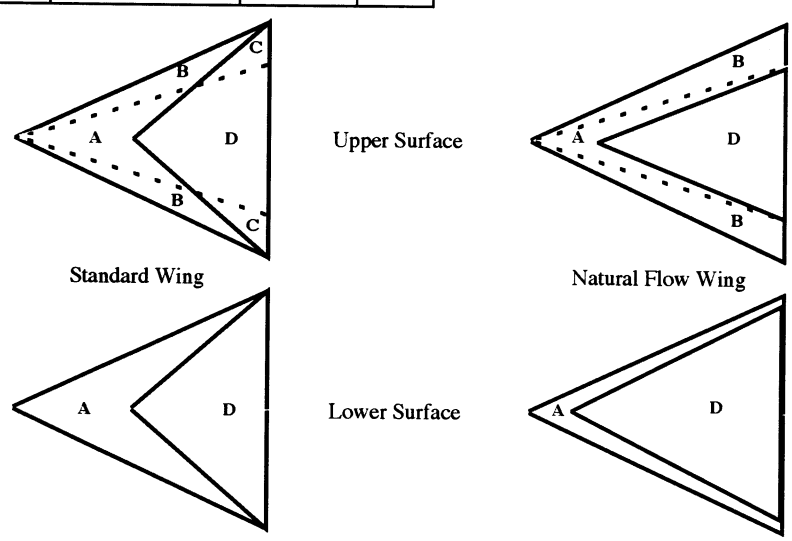



Figure 20. Supersonic aerodynamic loading characteristics for a typical delta wing and the natural flow wing design.

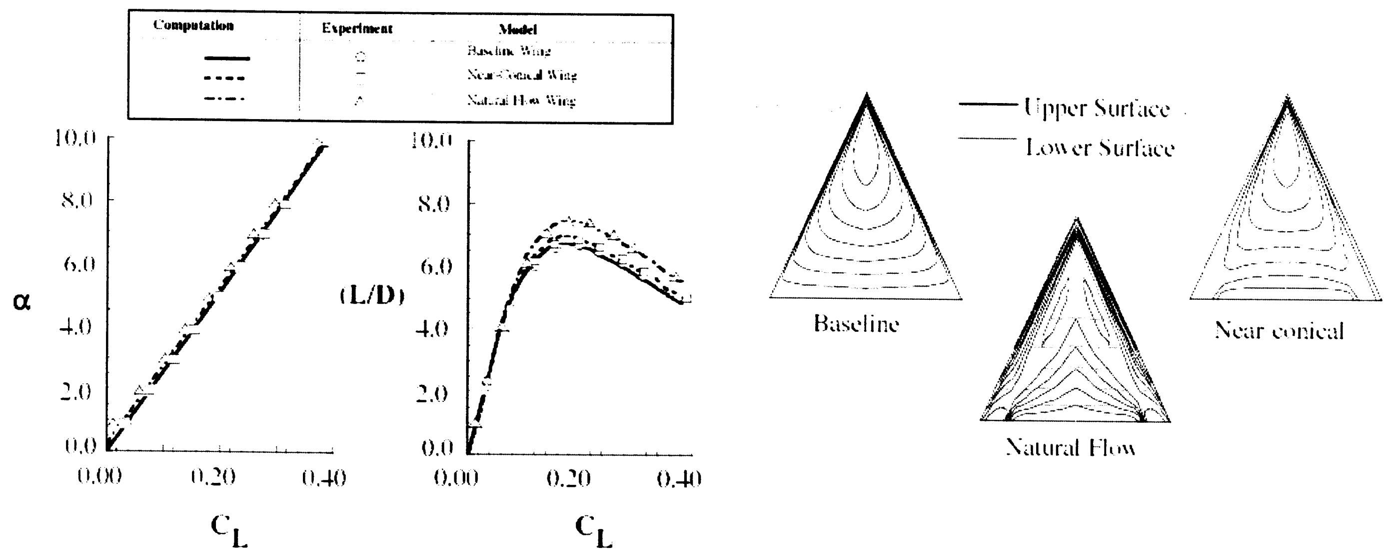



Figure 21. Details of the natural flow design geometry and supersonic aerodynamic performance

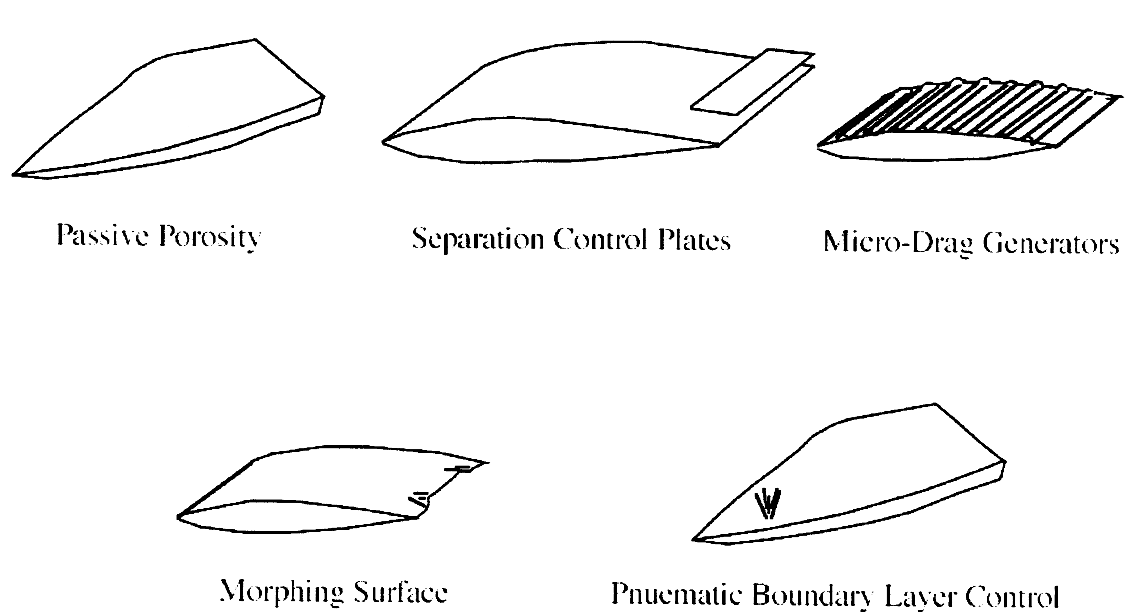



Figure 22. Graphic depicting various advanced aerodynamic control effector concepts.

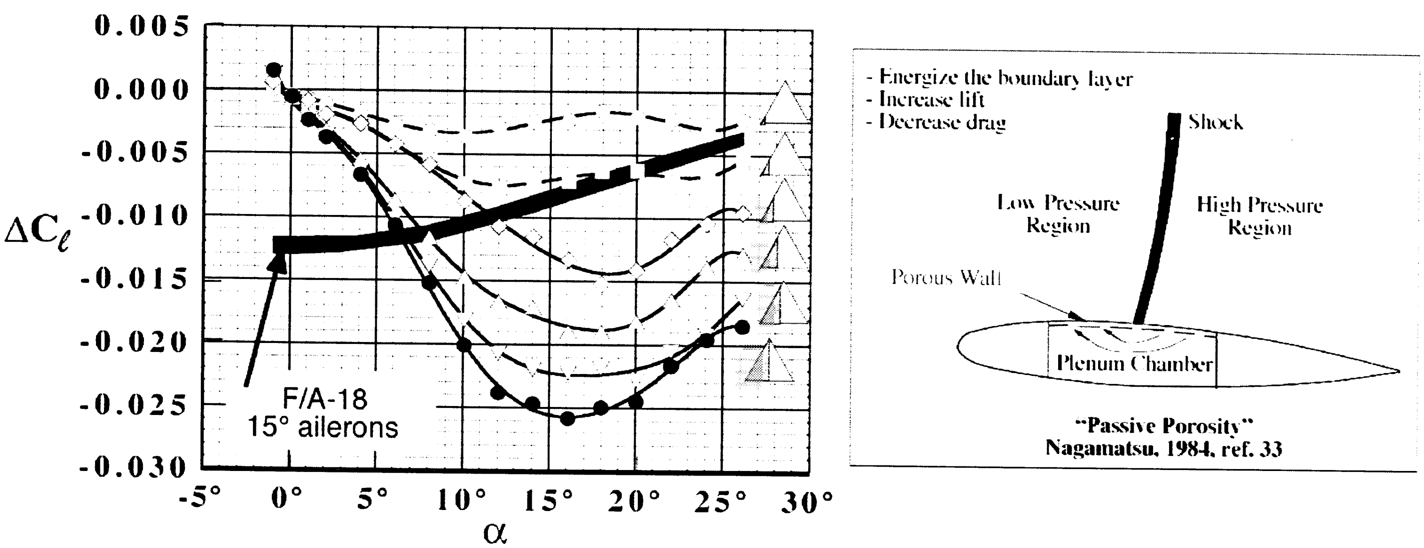



Figure 23. Details of the passive porosity control effector concept as applied to a wing.

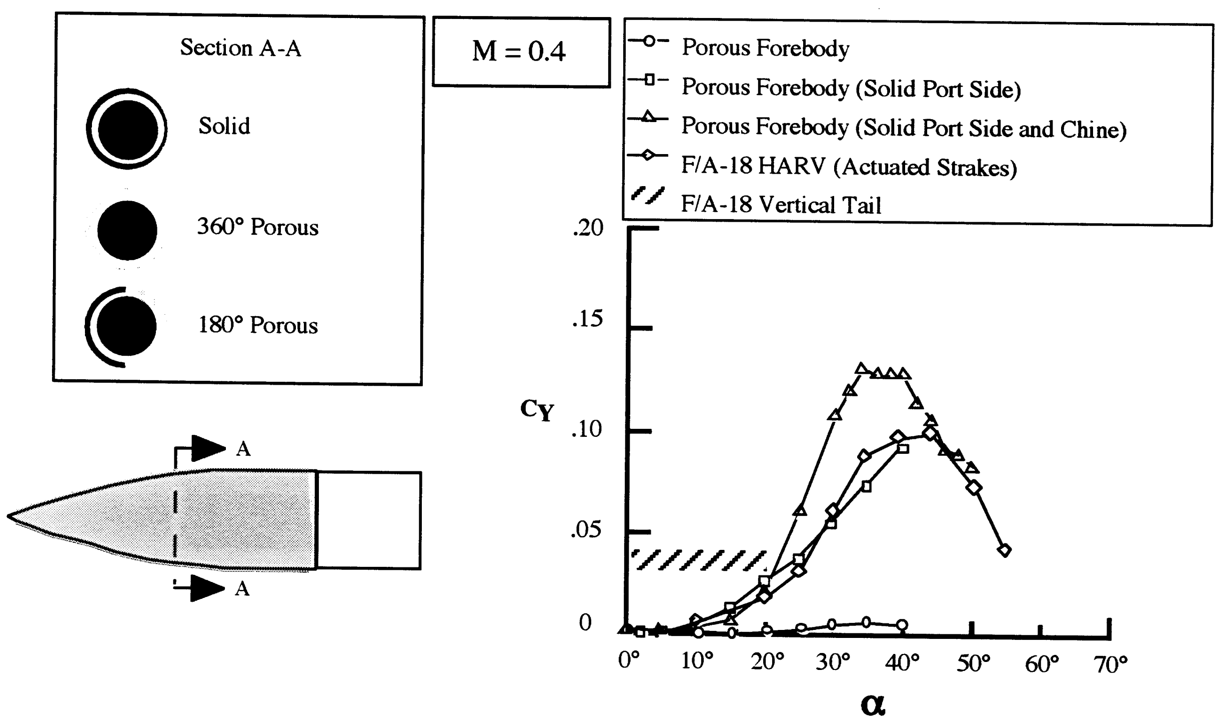



Figure 24. Details of the passive porosity control effector concept as applied to a forebody.

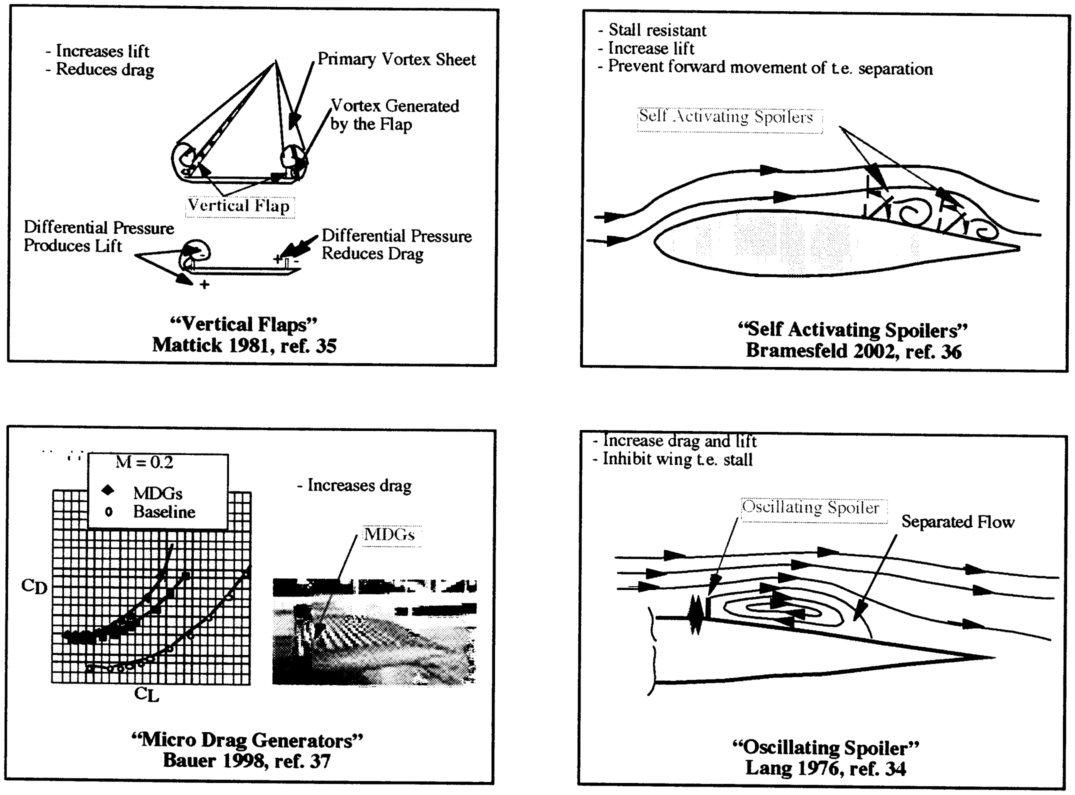



Figure 25. Graphic depicting four advanced mechanical aerodynamic control effector concepts,

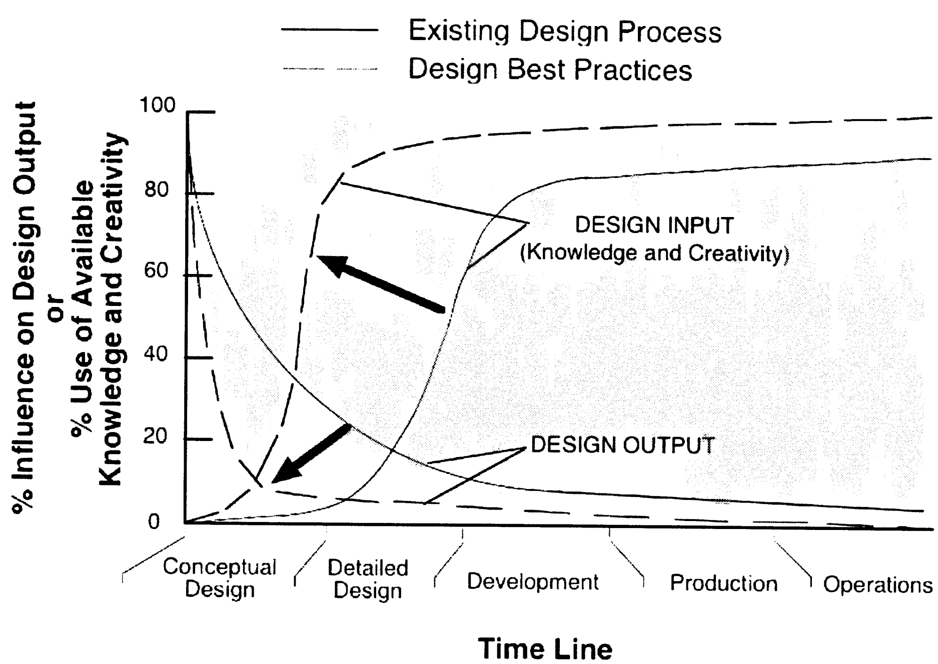



Figure 26. Graphic depicting a typical design time line.

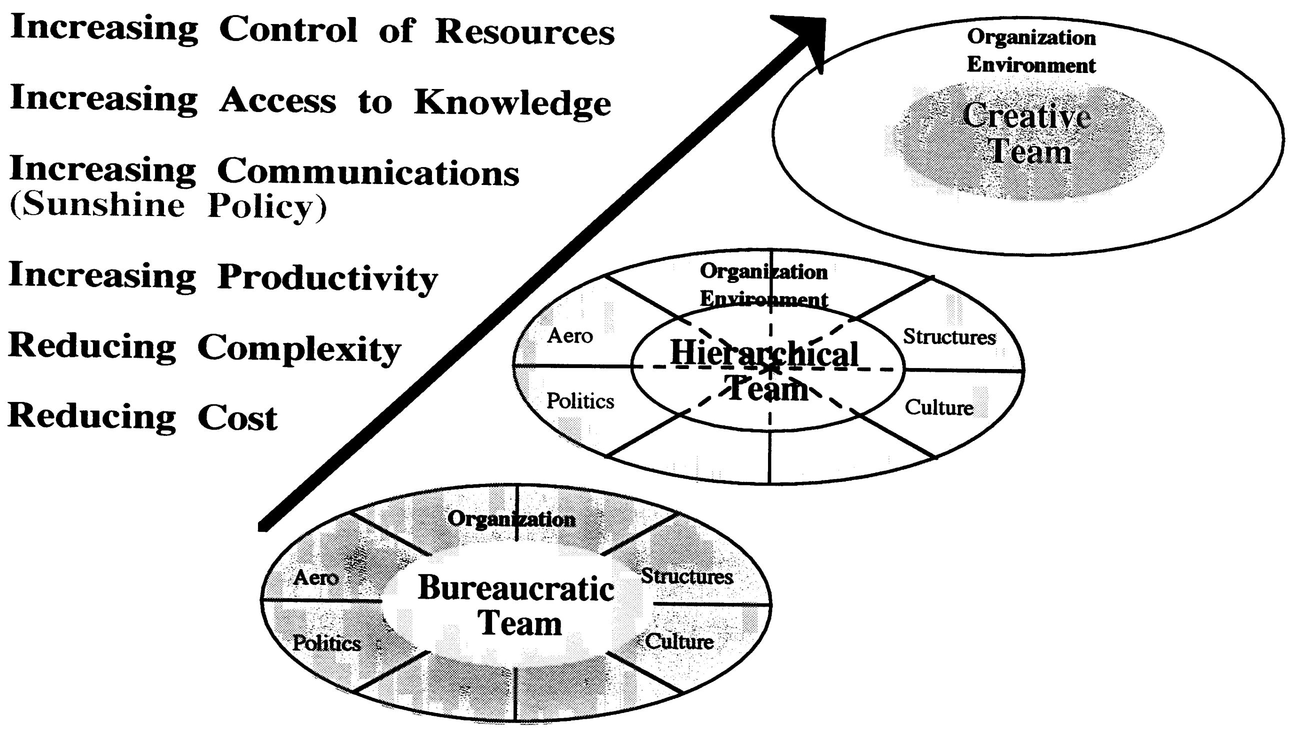



Figure 27. Graphic depicting three types of design team structures